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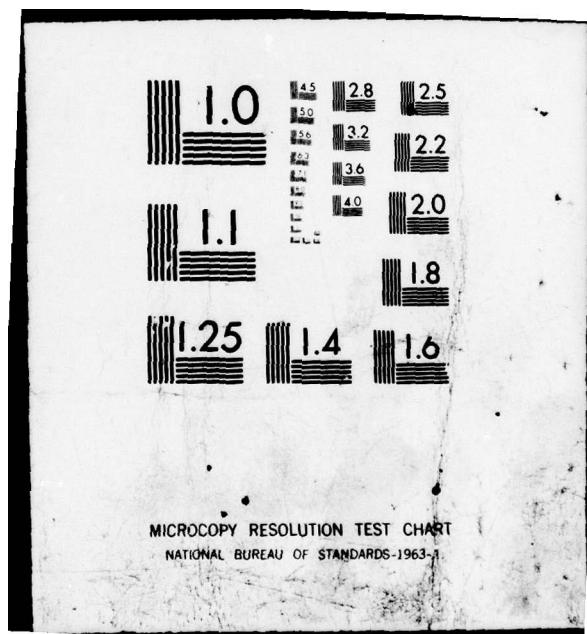
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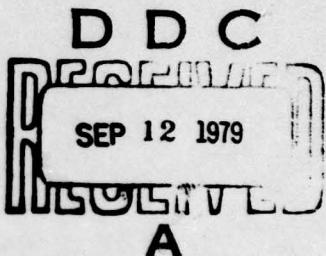
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LEVEL II

Resin Concrete for Bomb Damage Repair of Airfield Pavements

U S ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORY
P O BOX 4005
CHAMPAIGN, ILLINOIS 61820

NOVEMBER 1977



FINAL REPORT FOR PERIOD JANUARY 1976-FEBRUARY 1977

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CIVIL AND ENVIRONMENTAL
ENGINEERING DEVELOPMENT OFFICE
(AIR FORCE ENGINEERING AND SERVICES CENTER)

TYNDALL AIR FORCE BASE

FLORIDA 32403

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One type of liquid resin system, a highly reactive polyester, was shown to have the necessary properties. It came nearest to meeting all of the design objectives, including aggregate penetration, polymerization rate, early		

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strength development, ease of application, and cost.

To meet all of the design objectives, further studies of the identified material should focus on (1) material improvement in the areas identified as having performance weaknesses (e.g., bonding to wet aggregates), (2) repair patch designs which relate to composite material properties to patch size and subgrade support quality, and (3) application equipment criteria and design. However, the sponsoring agency recommends that new concepts be investigated rather than continue with further work on this particular resin system.

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PREFACE

This report documents work performed during the period January 1976 through February 1977 by the U.S. Army Construction Engineering Research Laboratory (CERL) under MIPR FQ 89527660007 from the Air Force Civil Engineering Center (AFCEC). On 8 April 1977, AFCEC was reorganized into two organizations. AFCEC became part of the Air Force Engineering and Services Agency. The R&D function remained under Air Force Systems Command as Det 1 (Civil and Environmental Development Office - CEEDO) HQ ADTC. Both units remained at Tyndall AFB, FL 32403. Captain Raymond S. Rollings was the Project Officer for AFCEC and CEEDO, and Mr. Alvin Smith was the Principal Investigator at CERL. The assistance of AFCEC and WES personnel in conducting the field tests is also gratefully acknowledged.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Raymond S. Rollings
RAYMOND S. ROLLINGS, Capt., USAF
Project Officer

Guy P. York
GUY P. YORK, Lt. Col., USAF
Director, Civil Engineering Development

Joseph S. Pizzuto
JOSEPH S. PIZZUTO Col., USAF, BSC
Commander

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SECTION I

INTRODUCTION

BACKGROUND

Paved areas used by aircraft represent a vital part of the capability of a USAF base. They are considered a prime target of the enemy during periods of conflict since rendering the pavement unusable either stops or severely limits the launching of aircraft. The result may be that grounded craft become highly vulnerable or that airpower support to other combat activities is suppressed. Techniques for rapidly repairing pavement and making it usable by tactical aircraft immediately after an attack are imperative to the successful mission of the US Air Force.

Numerous repair studies conducted in the past have emphasized the repair of large craters. The present USAF bomb-damage repair technique using aluminum mats was developed through testing at Eglin AFB, Florida (1962-1965). The technique has been tested under simulated conditions, and with revisions it is adequate for repairing large craters. New methods of crater repair, particularly for repair of numerous small craters, would be highly desirable. Objections to using the aluminum mat system for small craters are (1) the intermittent spacing of mats results in a very severe roughness profile for the aircraft, and (2) the time, manpower, and material required to put together and anchor a large number of mat groups are excessive (Reference 1).

A suggested technique for rapidly repairing small craters is to backfill the hole to a certain depth with crater ejecta, fill the rest of the crater with aggregate, and spray a liquid binder over the surface. The success of this technique depends on the properties of the binder, which would have to penetrate deeply enough into the aggregate to form a strong, durable, impact-resistant surface for aircraft operation. This repair technique is of particular interest to the Air Force because it could be used to repair a large number of small craters rapidly.

This study consisted largely of evaluating commercially available liquid resin systems. The numerous resin systems are identified by capitalized trade names throughout this report. Since the resin systems were used in this study for other than their intended purposes, the selection and rejection criteria used herein should not be considered as reflecting on the quality of the resins identified or their applicability to other uses.

OBJECTIVE

The objective of this study was to develop a rapid-curing resin concrete for use in repairing airfield pavements damaged by bombs. The goal was to identify a composite material which would attain sufficient strength in a short time to allow launching typical tactical aircraft such as the F-4 and F-111.

The specific goals of the study were:

- (1) Application of the resin to the aggregate and for cure to load-carrying capacity must be within 30 minutes for all temperatures between 35°F (2°C) and 125°F (51°C). The aggregate temperature will be the same as ambient temperature.
- (2) The resin concrete repair patch must sustain the launch of 50 tactical aircraft without repair. The design aircraft for the repair will be the F-4 (30 kip* load at 265 psi) and the F-111 (50 kip load at 150 psi). The design subgrade will have a modulus of subgrade reaction (k) of 100 lb/in³ or a California Bearing Ratio (CBR) of 3.
- (3) The aggregate quality requirements may not exceed ASTM C33-71 "Standard Specifications for Concrete Aggregate."
- (4) The repair cap will not exceed 1 foot (.3 meter) in thickness.
- (5) The resin concrete will use the minimum amount of resin possible, preferably no more than 15 percent by weight of aggregate.
- (6) The aggregate will be placed by dump trucks, spread by front-end loaders and dozers, and graded by a grader. No compaction will be done.
- (7) The liquid resin must be able to be both equipment mixed and sprayed and mixed and poured by hand upon the aggregate. When the resin is sprayed, both application and cure must be within 30 minutes. When the resin is poured by hand upon the aggregate, only the cure, after pouring, must be within 30 minutes.
- (8) The liquid resin must have a kinematic viscosity (ASTM D2170) between 40 and 120 centistokes for all temperatures between 35°F (2°C) and 125°F (51°C) to allow for spraying over the aggregate.
- (9) The resin must be able to displace free water in the aggregate, bond to wet aggregate, and cure to load-carrying capacity within 30 minutes.
- (10) All major components of the resin must have a minimum shelf life of 3 years at 72°F (22°C). All minor components must have a minimum shelf life of one year at 72°F (22°C). A major component is any material comprising 15 percent or more by weight or volume of the total mix of the resin and its components. Both major and minor components must be able to tolerate exposure to extremes (0° to 125°F [-17 to 51°C]) for 12 hours without degradation.
- (11) Storing and handling must not present unusual hazards for personnel or the environment.

* kip means 1000 pounds.

- (12) The cured resin concrete must be nonflammable and not susceptible to attack by petroleum products.
- (13) The repair patch must retain its serviceability despite natural conditions. Rapid loss of serviceability due to sunlight or freeze-thaw, for example, is unacceptable. Resistance to weathering should be comparable to or better than Portland Cement concrete or asphaltic concrete.
- (14) The repair patch must be able to be repaired by addition of extra aggregate and resin.
- (15) The cost of the resin and its components will not exceed \$20 per square foot of repair. For a 20-foot (6-meter) diameter repair, this is approximately the same cost as a 54-foot wide (16-meter) by 25-foot-long (7.5-meter) AM-2 patch. Obviously, an inexpensive resin is desired.

SCOPE

The study consisted of two phases. Only the first phase has been completed. AFCEC/CEEDO decided results of the first phase did not warrant continuation of the second phase and that another study of new concepts for rapid repair of runway pavements should be conducted.

The first phase consisted of the following steps:

1. Reviewing related bomb-damage repair (BDR) work identified by AFCEC
2. Surveying current literature and manufacturers to identify potential materials for investigation
3. Conducting screening tests of potential materials
4. Selecting the most acceptable materials
5. Conducting small field trials of the selected materials
6. Studying the feasibility of low-temperature (-32°C [-25°F]) repairs
7. Briefing AFCEC/CEEDO on the results of the study
8. Preparing a report if required by AFCEC/CEEDO.

The second phase was planned to include (1) any additional studies necessary to demonstrate conclusively that the composite would meet the requirements for BDR including repair patch design criteria, and (2) the conceptual design of equipment necessary for using the selected resin materials in BDR.

SECTION II

BACKGROUND STUDIES

REVIEW OF RELATED LITERATURE

A review of the procedural and historical work identified was conducted. To evaluate possible approaches to the design of a resin concrete as a repair cap material, it was necessary to become familiar with BDR procedures and past BDR work. Appendix A summarizes the AFCEC-specified references that were reviewed.

In addition, studies conducted in Great Britain and West Germany were reviewed. The British Ministry of Defence tested the use of liquid epoxy resins (Reference 2) and developed techniques for making scab repairs which successfully passed single-wheel load tests within 1 to 2 hours after placement. However, this method has been abandoned because of difficulty in obtaining consistent results and proper mixing in the field. The West Germans tested several organic binder materials and concluded that it is possible to repair bomb-damaged runways using resin concrete. They favor polyester or methylacrylate as a binder material.

The U.S. Army Engineer Waterways Experiment Station conducted a BDR study on both small and large craters and reported the suitability of using regulated-set cement concrete (Reference 3). Several field trials have been conducted. The repair procedures required specialized equipment, and the development of early strength occurred in about 90 minutes. Recent tests have given more satisfactory results.

The Civil Engineering Laboratory of the Naval Facilities Engineering Command has reported (Reference 4) favorable results of Dow Chemical Company studies directed toward assuring a long storage life (up to 5 years) for the polyester systems used in forming mats with fiberglass reinforcement capable of being landed upon by helicopter.

Studies conducted at the Bureau of Reclamation (Reference 5) suggest a novel approach to making and placing resin concrete. The resin and aggregate were mixed and placed by the shotcreting method normally used for Portland cement concrete. The resin (a vinyl ester) was mixed with the aggregate near the nozzle of a pneumatic delivery line. Rapid curing for 5 to 10 minutes produced compressive strengths of about 13,400 psi (91 MPa) with a resin content of 13 to 20 percent by weight.

Numerous texts and journals on polymers were reviewed, but little pertinent information was gained. Since research has not addressed the complexities involved in the property and performance specifications for resins and for resin concretes for BDR operations to any appreciable extent, little engineering information has been published. The use of resin concretes for repair of highway pavements or bridge decks is well documented and many commercial products are available. However, these materials are used in considerably more leisurely situations and the installation conditions are more easily controlled. Consequently, these materials are not directly appropriate for BDR work.

Based on the literature survey and experience, liquid resin systems of the epoxy, polyester, polyurethane, phenolic, acrylic, and furane types were considered the most feasible for forming resin concretes. These polymer families were selected because of availability, cost, and performance in other applications. For example, acrylics, epoxies, polyesters and polyurethanes have been used in soil stabilization and consolidation and in polymer concretes. Phenolics and furanes are used as binders in foundry sand castings. Furanes are used in soil stabilization in sidewalls of drilled wells. Other liquid resin systems such as the silicones, glyptals, polyimides, urea-formaldehyde and phenol-aralkyl resins were not considered feasible due to cost, toxicity, or inappropriate methods of inducing cure in the anticipated use.

MANUFACTURERS CONTACTED

Resin system manufacturers or suppliers selected from the Modern Plastics Encyclopedia were contacted. The requirements of the materials were discussed and many suggestions were obtained. Table 1 lists the companies contacted and the type of resin produced and indicates whether the company expressed interest in the present study. Appendix B lists the manufacturers' addresses and telephone numbers.

TABLE 1. MANUFACTURERS CONTACTED

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Abatron	Epoxy	yes	no*	
Abbott	Epoxy	no		
Ablestik	Epoxy	no		
Acme Chemical	Epoxy	yes	no	
Acme Resin	Phenolic	no		
Adhesive Engr.	Epoxy	yes	yes	CONCRESIVE
Adhesive Prod.	Urethane	yes	no	
Akemi	Epoxy	yes	no	
Allaco	Epoxy	yes	no	
Allied	Epoxy	no		
Alpha	Polyester	yes	yes	ALTEK
Amer. Cyanamid	Polyester	yes	yes	LAMINAC
Amer. Resin	Epoxy	yes	no	
Amicon	Epoxy	yes	yes	XT-1374
Anderson	Urethane	yes	yes	ANDUR-9000-AS
Anhydrides & Chem.	Epoxy	no		
Applied Plastics	Epoxy	no		
Armstrong	Epoxy	yes	no	
Atlas	Furan	no		
Axel	Acrylic	no		
BASF Wyandotte	Urethane	yes	no	

* A "no" in this column indicates that the company decided, after review of the requirements, that it did not have a suitable product.

TABLE 1. MANUFACTURERS CONTACTED (CONTINUED)

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Beacon	Epoxy	no		
Berton	Epoxy	no		
Bishop	Epoxy	no		
Bostik	Acrylic	no		
Cadillac	Acrylic	no		
Cal Polymers	Urethane	yes	yes	
Carlson	Epoxy	no		
Castall (Allied)	Epoxy	yes	no	
Celanese Coatings	Acrylic	yes	no	
Celanese Resins	Epoxy	yes	yes	EPI-REZ/EPICURE
Chem. Coatings	Epoxy	yes	no	
Chem. Engr. Ass.	Urethane	no		
Chem. Prod.	Urethane	yes	no	
Ciba-Geigy	Epoxy	yes	no	
Claremont	Urethane	yes	no	
Conap	Epoxy	yes	no	
Cook	Polyester	yes	no	
Daubert	Acrylic	yes	no	
Deer	Acrylic	no		
Dennis	Epoxy	yes	no	
Devcon	Acrylic	yes	no	
Diamond	Polyester	yes	no	
Dow	Epoxy	yes	yes	DER 331 DER 732

TABLE 1. MANUFACTURERS CONTACTED (CONTINUED)

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Dupont	Acrylic	no		
Durez	Furan	no		
Dynamit	Furan	no		
Emerson & Cuming	Epoxy	yes	no	
Eronel	Furan	no		
Fenwal	Epoxy	yes	no	
Flexcraft	Acrylic	yes	no	
Formulated	Acrylic	yes	no	
Freeman	Polyester	yes	no	
Freeman	Urethane	yes	no	
Fuller	Epoxy	yes	no	
Furane	Epoxy	yes	no	EPOCAST 530
General Electric	Phenolic	no		
Georgia Pacific	Phenolic	no		
Goodrich	Urethane	yes	no	
Grace	Polyester	yes	yes	GR 135
Hardman	Epoxy	yes	no	
Hastings	Urethane	yes	yes	1600-1A
Hauthaway	Acrylic	no		
Heil	Urethane	no		
High Strength	Epoxy	no		
Hightemp	Epoxy	no		
Hommel	Epoxy	no		
Hunt	Epoxy	no		

TABLE 1. MANUFACTURERS CONTACTED (CONTINUED)

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Hysol	Epoxy	no		
Inolex	Urethane	no		
Interplastic	Polyester	yes	no	
IPRC	Urethane	yes	no	
Ironsides	Phenolic	no		
Isochem	Urethane	yes	no	
Jedco	Acrylic	no		
Key Polymer	Acrylic	yes	no	
Koppers	Polyester	yes	no	
Kristal Kraft	Epoxy	yes	no	
Leepoxy	Epoxy	yes	no	
M R Plastics	Epoxy	yes	no	
Metachem	Epoxy	yes	no	
Midwest Urethane	yes	no		
Miller-Stephenson	Epoxy	yes	yes	
Mitchell Rand	Epoxy	yes	no	
Mobay	Urethane	yes	no	
Mol-Rez	Polyester	yes	no	
Monsanto	Phenolic	no		
N.L. Industries	Urethane	no		
Olin	Urethane	no		
Pacific Resins	Phenolic	no		
Palmer	Epoxy	yes	no	
Plastics Engr.	Phenolic	no		

TABLE 1. MANUFACTURERS CONTACTED (CONTINUED)

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Polymer Systems	Urethane	no		
Polyproducts	Epoxy	yes	yes/21-116	POLYPRODUCTS/ 21-116/20-100/ 21-116
Poly Resins	Epoxy	yes	no	
3-M	Epoxy	yes	no	
Tra-Con	Epoxy	yes	no	
Union Carbide	Epoxy	yes	no	
Uniroyal	Urethane	yes	no	
U.S.-Gypsum	Epoxy	yes	no	
U.S. Polymeric	Urethane	yes	no	
Upjohn	Urethane	yes	no	
Varni-Lite	Epoxy	yes	no	
Vernon-Binshoff	Acrylic	no		
Verona	Urethane	no		
Witco	Urethane	no		
Laticrete	Epoxy	yes		
Radiation Tech.	Polyester	yes	yes	RADGROUT H and J-27
Micor	Epoxy	yes		
Schaefer	Epoxy	yes	yes	SCHAEFER 100-L6
Preco	Polyester	yes	yes	PRECO GOLD LABEL
Polyrez	Phenolic	no		
PPG Industries	Polyester	yes	yes	SELECTRON [®]
Procter & Gamble	Epoxy	no		

TABLE 1. MANUFACTURERS CONTACTED (CONCLUDED)

Company	Resin Type	Initial Interest	Material Evaluated	Product Name
Purethane	Urethane	yes	no	
Permuthane	Acrylic	yes	no	
Quaker Oats	Furan	no		
Quinn	Urethane	yes	no	
Reichhold	Epoxy	yes	yes	37-127 & 37-627
Ren Plastics	Epoxy	yes	no	
Roberts, E.V.	Epoxy	yes	no	
Royston	Urethane	yes	no	
Ruco	Urethane	yes	no	
Shell	Epoxy	yes	yes	EPON 828
Silmar	Polyester	yes	no	
Smooth-On	Epoxy	no		
Solar	Epoxy	no		
Sta-Crete	Epoxy	yes	no	
Stanchem	Urethane	yes	no	
Sterling (Reichold)	Epoxy	yes	yes	STERLING Y297-83
Stonhard	Epoxy	yes	no	
Sullivan	Polyester	no		
Synres	Polyester	yes	no	
Techform	Epoxy	yes	no	
Tennant	Epoxy	no		
Thalco	Epoxy	no		

SECTION III

MATERIALS STUDIES

AGGREGATE STUDIES

The aggregates used in the studies were restricted to those meeting all the requirements of ASTM C-33-74, "Standard Specifications for Concrete Aggregate," except the grading requirements. Such a restriction assures the use of sound, clean material with the resin.

The size of the aggregate particles was significant since the resin is required to flow downward by gravity through the void spaces of the aggregate. Studies of the effect of aggregate size and gradation on void space were conducted and related to the ability of the resin to penetrate readily.

As reported by Goldbeck (Reference 6), there is less than a 10 percent spread in the percentage of void space resulting from mixing three different gradations of crushed limestone. In 66 combinations of the three grades ranging in size from 1/8 to 2 1/2 inches (3.1 to 63.5 mm) the void space range was from 38.6 to 47.3 percent. A similar void space exists in natural gravel. By mixing grades from No. 4 (sieve) to 2.0 inches (50.8 mm), a minimum of 31 percent void space can be attained in rodded natural gravel. Powers (Reference 7) related solid volume, angularity, size ratio, and particle geometry of aggregates to the void space. It was found that a minimum void space of about 25 percent could be achieved by co-mixing various grades of coarse aggregates.

Laboratory studies confirmed the reported values; the void percentage in mixtures of No. 4 to 3/4-inch (19-mm) crushed limestone (unrodded) ranged from 43 to 47 percent. The studies were performed using ASTM C30-37, "Standard Method of Test for Voids in Aggregate for Concrete."

Mixtures of coarse 3/4-inch (19-mm) aggregate and fine (sand) aggregate were designed to give a 25 percent void volume. A mixture of 65 percent coarse and 35 percent fine aggregate (by weight) provides the desired void volume. Such mixtures, as well as other coarse/fine aggregate mixtures, are not considered applicable to BDR where resin permeation is to be only by gravity flow. The high surface area and small void sizes prohibit adequate penetration, resulting in puddling of resin on top. No resin reaches the lower area of the aggregate. In addition, stockpiling of mixed aggregates poses another problem. Handling of such mixtures tends to cause rapid separation of the different grades into rough stratum levels with the finest material settling to the bottom and the coarsest floating to the top. Therefore, it was concluded that for the purposes of BDR, a single uniform gradation of either crushed stone or natural gravel of approximately 3/4 inch (19 mm) (passing the 3/4 inch [19 mm] and retained on the 1/2 inch [13 mm] sieve) would allow most expedient handling and ensure adequate resin penetration by typical commercial liquid resin systems. Accepting the higher void content was a necessary trade-off. The 1/2- to 3/4-inch (12- to 19-mm) aggregate is a good compromise between satisfactory resin penetration and surface roughness of the repair patch.

RESIN STUDIES

Liquid resins from three family types were evaluated as binders and matrix materials for BDR resin concretes. Initially, epoxy, glyptal, polyester, polyimide, polyurethane, urea formaldehyde, acrylic, silicone, furane and phenol-aralkyl resins were considered as having potential. Based on discussions with technical representatives from the various companies supplying these families of resins, only the epoxy, polyester, and polyurethane types showed promise for BDR use. Samples of the selected materials were either supplied by the companies or were purchased. Only those materials suggested by the manufacturers or suppliers were evaluated, as it was felt that the manufacturer's technical representatives would best know the potential of their materials for meeting the stated requirements. A few manufacturers offered to conduct studies to develop a resin system which would meet the criteria, but they were declined because that approach did not fall within the scope of this study.

The first step in the resin studies was to evaluate the gel time at the temperature extremes and at a point about midway between them. One-hundred-gram batches of neat resins (containing no fillers) were prepared according to the manufacturer's directions. The resin components were conditioned to the test temperature for at least 12 hours prior to the test. The tests were conducted at temperature levels of 35° F (2°C), 75° F (24°C) and 120° F (49°C) as specified.

Standard gel-time measurements require preparing a known mass of resin system (usually 100 grams) and conducting the gelation in a controlled elevated-temperature bath. Since this procedure was not applicable, an alternate method was employed. The end of a hardwood splint was touched to the mass surface and pulled away. Gelation was determined to have occurred at the stated test temperature when the splint would no longer withdraw a string of material. This method was used throughout the study to measure gel time.

All of the resins evaluated were exothermic during the reaction stage. In the neat 100-gram batches, the peak exothermic temperatures reached were noted, but it was decided that this information would not be pertinent when the resin was mixed with aggregate. The short-gel-time, fast-curing resins all exhibit high peak exotherms, typically from 342° F (150°C) to 488° F (220°C), because of the rapidity with which reaction takes place. The peak temperature normally observed depends on the initial temperature of the ingredients, the number and type of chemical bonds formed, and the quantity and geometry of the reacting mass. Since rapid curing to load-carrying strength was an objective of the study, no effort was made to decrease the polymerization exotherm. Figures 1 through 4 show some of the neat resin test batches and the thermal cracking which often occurs in highly reactive systems.

Following the neat resin experiments, tests were conducted in which the resin was cured in contact with wet and dry aggregates. The gel time was noted for comparison to the neat resin gel time. The work was carried out at the same temperatures used for the neat resin tests. Both the resin materials and the aggregates were conditioned to the test temperature.

The test procedure consisted of preparing a 100-gram batch of each resin system and pouring it on top of aggregate contained in a cardboard cylinder 3 inches (76.2 mm) in diameter by 6 inches (152.4 mm) high (Figure 5). The aggregate mass was about 2 lb (900 grams) in each case; thus, the resin constituted about 11 percent by weight. After the resin was cured, the cardboard forms were stripped away and the amount of penetration and the completeness of aggregate coating was observed. Table 2 lists materials, the mix proportions, and the gel times of the resins under various conditions. A subjective evaluation of the viscosity of the resin materials at the different temperatures is also given. Figure 6 indicates the varying degrees of resin penetration obtained.

The viscosity of the resins was measured with a Brookfield viscosimeter at 50 and 100 rpm using a No. 4 spindle. The relationship between viscosity at the application temperature and the aggregate size shows that for most materials a viscosity of 15,000 centipoises (15,000 mPa.s) should not be exceeded if the resin is to penetrate 3/4-in. (19-mm) uncompacted aggregate. Smaller aggregate with smaller open spaces slows the rate of permeation, and the more viscous materials tend to trap and hold air pockets. For partial filling of voids, low-viscosity resins tend to drain down too readily and to leave insufficient resin on the aggregate to effect good bonding between particles.

Table 2 also indicates that the gel time is temperature dependent. All of the resins evaluated gelled more rapidly at the upper temperature extreme than at the lower one. Aggregates retarded the gelation by absorbing heat from the resin system. This effect was more pronounced in wet aggregates than in dry ones. There was evidence that the free water in some systems interfered with or retarded the chemical processes, affecting the foaming of polyurethanes and producing long-term rubberiness in some of the epoxies. Figure 7 shows the polyurethane foaming phenomenon, and Figures 8 and 9 show the failure of some epoxies to cure when in contact with wet aggregate.

As anticipated, free moisture on the aggregate severely restricted chemical bonding of the resin to the aggregate particles. In the zone of the specimens where the entire void volume was filled with a resin matrix, the complete encapsulation provided mechanical strength even though bonding to the aggregate was not good.

The systems which gelled fastest were evaluated to ascertain potential usefulness at very low temperatures. The various constituents of the resin systems indicated in Table 2 as having gelled at 35°F (2°C) in 20 minutes or less and selected other systems were conditioned to -25°F (-4°C). Table 3 indicates the results of this conditioning.

It is not feasible to use any of the liquid resins evaluated if they are conditioned to very low temperatures since one or more of the components freezes or becomes too viscous to mix and pour. The resins all reacted and gelled normally when allowed to return to room temperature. It was concluded that exposure to low temperatures is not harmful to the resins but they cannot be mixed and applied when very cold.

TABLE 2. GEL TIME TEST RESULTS

RESIN TYPE	PRODUCT	PERCENT BY WEIGHT RESIN	2°C**			24°C**			50°C			REMARKS
			NEAT DRY* GEL TIME HR MIN	WET* GEL TIME HR MIN	NEAT DRY* GEL TIME HR MIN							
E	EPICURE 50727 (EPICURE 874)	82	18	0 - 4	0 - 5	0 - 7	0 - 2	0 - 5	0 - 6			Too reactive to hand mix at elevated temperature. Moderate cost.
U	1600-1A	50	50	0 - 5	0 - 25	0 - 45	0 - 4	0 - 15	0 - 6	0 - 6	0 - 2	Viscosity low at low temperatures; reacts with water and foams.
S	LAMINAC 4128	98	2	0 - 7	0 - 17	0 - 23	0 - 3	0 - 12	0 - 15	0 - 4	0 - 6	Good in all tests; high exotherm (about 200°C). Low cost.
E	XT-1374-A	85	15	0 - 8	0 - 13	0 - 37	0 - 4	0 - 7	0 - 10			Small sample, unable to procure working quantity.
S	SELECTION RS-50149	99	1	0 - 10	1 - 10	8 -	0 - 5	0 - 25	0 - 27			Low viscosity, very reactive.
E	20-100 21-116	67	33	0 - 10	0 - 24	1 - 20	0 - 6	0 - 10	0 - 10	0 - 4	0 - 5	High viscosity; sensitive to slight errors in mix proportions and mixing. Remains rubbery for several hours when applied to wet aggregate. High cost.
E	21-116	50	50	0 - 15	0 - 23	0 - 35	0 - 5	0 - 10	0 - 10	0 - 4	0 - 4	0 - 4

*Aggregate moisture--surface dry or surface wet.

**Temperature stated is that of both resin and aggregate.

(1) Typical composition--90 percent aggregate by weight + 10 percent resin by weight.

E = Epoxy

U = Urethanes

S = Polyesters

TABLE 2. GEL TIME TEST RESULTS (CONTINUED)

RESIN TYPE	PRODUCT	20°C**				24°C**				50°C			
		NEAT GEL TIME HR MIN	DRY* GEL TIME HR MIN	WET* GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN
S	J27	98	2	0 - 15	1 - 31	1 - 50	0 - 5	0 - 15	0 - 20				Medium-fast reaction; high cost.
S	J27	99	1	0 - 20	1 - 57	2 - 0	0 - 4	0 - 17	1 - 47				
S	CONCRESSIVE 1221-1217	60	0	25	1 - 10	2 - 45	0 - 7	0 - 40	0 - 45	0 - 3	0 - 13	0 - 14	Good road-patch material; too slow for BDR. Requires mixing with aggregate.
E	CONCRESSIVE 1217-1221	60	40	0 - 25	1 - 30	2 - 25	0 - 7	0 - 30	0 - 30	0 - 3	0 - 11	0 - 13	
E	CONCRESSIVE 1221-1221	60	40	0 - 25	2 - 5	3 - 10	0 - 9	1 - 10	1 - 5	0 - 2	0 - 12	0 - 18	
S	RADGROUT-H	98	2	0 - 30	1 - 25	1 - 42	0 - 5	1 - 5	1 - 15				Viscous at low temperature.
E	SCHAFFER 107	67	33	0 - 35	3 - 45	1 - 45	0 - 7	0 - 30	0 - 30	0 - 4	0 - 11	0 - 12	
E	CONCRESSIVE 1217-1217	60	40	0 - 35	0 - 45	1 - 45	0 - 7	0 - 30	0 - 30	0 - 4	0 - 11	0 - 12	
S	SELECTRON 50/29	99	1	0 - 35	2 - 5	2 - 15	0 - 12	0 - 23	0 - 55				
S	ALTEK-37-M	94	6	0 - 35	1 - 5	1 - 20	0 - 7	0 - 22	0 - 27				Requires heat or more reactive cat- alyst system.

* Aggregate moisture--surface dry or surface wet.

** Temperature stated is that of both resin and aggregate.

(1) Typical composition--90 percent aggregate by weight + 10 percent resin by weight.

E = Epoxy

U = Urethanes

S = Polyesters

TABLE 2. GEL TIME TEST RESULTS (CONTINUED)

RESIN TYPE	PRODUCT	PERCENT BY WEIGHT RESIN/HARD.	2°C**			24°C**			50°C			REMARKS
			NEAT GEL TIME HR MIN	DRY* GEL TIME HR MIN	WET* GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY* GEL TIME HR MIN	WET* GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY* GEL TIME HR MIN	WET* GEL TIME HR MIN	
S	RADGROUT-H	99	1	0 - 37	1 - 45	1 - 58	0 - 4	0 - 40	0 - 45			
	ANUR-9000-AS	50	50	0 - 40	2 - 45	8 -	0 - 12	2 - 15	2 - 5	0 - 4	0 - 16	0 - 25 Reacts w/ -77°F aggr.
E	DOM 331	80	20	0 - 45	8 -	8 -	0 - 10	1 - 7	1 - 10			Tac S. 100
E	1000 L6	67	33	0 - 55	2 - 45	>8 -	0 - 13	2 - 0	1 - 30	0 - 2	0 - 11	Tac S. 100
S	Preco Pt. A	98	2	1 - 0	1 - 45	1 - 55	0 - 8	0 - 15	0 - 17	0 - 6	0 - 10	Tac S. 100
	REINHOLD 37-140/37-627	67	3 - 5	>8 -	>8 -	>8 -	0 - 35	3 - 10	3 - 40	0 - 0	0 - 30	0 - 35 Very slow at temperatures
E	SCHAFFER 107	74	26	3 - 35	>8 -	>8 -	0 - 25					Very slow at temperatures
E	Y29-83 C85/84-014	83	17	4 - 25	>8 -	>8 -	0 - 25	2 - 30	3 - 25	0 - 4	0 - 14	0 - 22 Very slow at temperatures
E	REINHOLD 37-140/37-605	77	23	4 - 30	>8 -	>8 -	0 - 30	3 - 0	3 - 10	0 - 7	0 - 43	0 - 46 Very slow at temperatures
E	Y29-83 C85 & C46	83	10	7	>8 -	>8 -	0 - 53	3 - 40	3 - 40	0 - 15	0 - 55	1 - 1 Extreme low temp. res.

* Aggregate moisture--surface dry or surface wet.

** Temperature stated is that of both resin and aggregate.

(1) Typical composition--90 percent aggregate by weight + 10 percent resin by weight.

E = Epoxy

U = Urethanes

S = Polyesters

TABLE 2. GEL TIME TEST RESULTS (CONCLUDED)

RESIN TYPE	PRODUCT	PERCENT BY WEIGHT RESIN	2°C**				24°C				50°C**				REMARKS
			NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	NEAT GEL TIME HR MIN	DRY GEL TIME HR MIN	WET GEL TIME HR MIN	
E	REICHHOLD 27-127/37-605	77 23	>8 -	>8 -	>8 -	0 - 58	5 - 10	5 - 20	0 - 17	0 - 55	1 - 55	1 - 5	1 - 5	1 - 1	Extremely slow at low temperatures.
E	REICHHOLD 37-127/37-627	67 33	>8 -	>8 -	>8 -	1 - 0	5 - 15	5 - 25	0 - 14	1 - 5	1 - 10	1 - 10	1 - 10	1 - 10	Extremely slow at low temperatures.
E	SCHAFFER 100-L6	74 26	>8 -	>8 -	>8 -	1 - 7	4 - 45	4 - 55	0 - 10	0 - 50	0 - 55	0 - 50	0 - 55	0 - 55	Extremely slow at low temperatures.
E	Y297-83 C85 & C46	83 10	>8 -	>8 -	>8 -	2 - 48	5 - 5	5 - 15	0 - 15	0 - 56	1 - 56	1 - 56	1 - 56	1 - 56	Extremely slow at low temperatures.
E	EPOCAST 530	80 20	>8 -	>8 -	>8 -	7 - 0	8 -	8 -	0 - 45	1 - 30	1 - 43	1 - 30	1 - 43	1 - 43	
E	EPOCAST 530	75 25	>8 -	>8 -	>8 -	0 - 12	1 - 20	2 - 57							
E	DNW 331	56 24	>8 -	>8 -	>8 -	0 - 15	1 - 20	3 - 50							
E	DNW 732	20													

* Aggregate moisture--surface dry or surface wet.

** Temperature stated is that of both resin and aggregate.

(1) Typical composition--90 percent aggregate by weight + 10 percent resin by weight.

E = Epoxy

U = Urethanes

S = Polyesters

TABLE 3. LOW-TEMPERATURE RESIN EVALUATION

Resin System	Remarks	
EPIREZ 50727	viscous	froze
EPICURE 874		
HASTINGS 1600-1A	one component	very viscous 100,000 cps (mPa.s)
LAMINAC 4128	viscous	50,000 cps (mPa.s)
Promoter: CN*	froze	
Catalyst: MEKP*	froze	
XT1374-A	froze	
SELECTRON RS-50149 (Prepromoted)	viscous	50,000 cps (mPa.s)
Catalyst: MEKP	froze	
Polyproducts 20-100	froze	
Polyproducts 21-116	froze	
RADGROUT J27	viscous	50,000 cps (mPa.s)
Catalyst: MEKP	froze	
Dow 331	froze	
Dow 732	viscous	50,000 cps (mPa.s)
Furane 946	very	100,000 cps (mPa.s)
EPOCAST 530	froze	
Hardener 946	viscous	100,000 cps (mPa.s)
ALTEK 37-M	viscous	50,000 cps (mPa.s)
Promoter: Dimethylaniline	froze	
Catalyst: Benzoyl Peroxide		
ALTEK 37-M	viscous	50,000 cps (mPa.s)
Promoter: CN	froze	
Catalyst: MEKP	froze	

* CN is cobalt naphthanate (6 percent Co)

** MEKP is methyl ethyl ketone peroxide

In a second series of low-temperature studies the resin materials were maintained and mixed at room temperature 75°F (24°C) and then poured over the aggregate which had been conditioned at -25°F (-4°C). After introduction of the resin, the specimens were left at room temperature 75°F (24°C) until gelation occurred. The tests were conducted in the same manner as the earlier gel time tests. Table 4 shows the results of these tests.

The absorption of heat from the resin mix by the aggregate retards the reaction rate. However, it was concluded from this study that the potential for making resin concrete for low-temperature BDR work is good provided that the resin is stored at a controlled temperature of about 50°F (10°C) or higher. In some resin systems, such as the polyester and polyurethane types, the amount of catalyst can be increased to speed up the gelling and curing of the resin at low temperatures. These studies did not address the exact reformulation required.

The resin studies show that some highly reactive, high-exotherm systems can gel in the required time, can penetrate the selected aggregate, and can be used in the temperature range of interest if the resin is maintained at 50°F (10°C) or higher. The approximate maximum limiting viscosity of the resin at the application temperature is 15,000 centipoise (15,000 mPa.s).

TABLE 4. ROOM-TEMPERATURE RESIN ADDED TO LOW-TEMPERATURE AGGREGATE

Resin System	Resin Temperature, °F (°C)	Aggregate Temperature, °F (°C)	Gel Time Hr	Time Min
EPI-REZ 50727	74 (23)	-25 (-32)	0	30
EPICURE 874				
HASTINGS 1600-1A	74 (23)	-25 (32)	0	14
LAMINAC 4128	74 (23)	-25 (32)	0	25
Polyproducts 20-100	74 (23)	-25 (32)	0	30
EPOCAST 530 Hardener 874	74 (23)	-25 (-32)	0	45
Dow 331	74 (23)	-25 (-32)	1	30
Dow 732				
D.E.H. 29				

SECTION IV

FLEXURAL STRENGTH TESTS

The performance of a repair patch depends on the flexural strength of the patch material. Flexural strength tests were conducted on 6 x 6 x 21 inch (152 x 152 x 533 mm) beams in accordance with ASTM C-78 (18 inch [457 mm]) spans and third point loading).* The beams were prepared by placing aggregate in a mold and pouring mixed resins on top of the aggregate. Resin/sand mixtures were applied to the top of the beam in the upper load-point areas to provide a reasonably smooth surface.

Resins which showed the most promise in the previous studies were used in the flexural tests: EPI-REZ 50727/EPICURE 874, LAMINAC 4128, HASTINGS 1600-1A, POLYPRODUCTS 20-100/21-116, and EPOCAST 530. In the initial tests, 15 percent resin (by weight of aggregate) was poured over the aggregate and allowed to flow by gravity down through the aggregate. As in the case of the cylinders, some resin reached the bottom of the mold and completely filled the void space in the lower 1 to 2 inches (25 to 50 mm). The specimens were prepared in groups of three. Each specimen was made with a weighed batch of resin. For each material tested, one series of beams was made with dry aggregate and one with wet aggregate. The first series of beams was made at 68°F (20°C) and tested at that temperature.

In most cases, the first beam in each series was tested within 45 minutes after the resin was poured. In a few cases where the resin was too rubbery at that age to test, the initial test was performed as soon as the beam would accept a load. A second beam from each batch was tested 1-1/2 hours after resin application. The third beam was tested 3 hours after resin application.

At the short test time, most fractures occurred in the resin matrix, but at the intermediate and long test times fracture through the aggregate was prevalent. Bonding was obviously better (in all cases) between the resin and dry aggregate, as evidenced by the aggregate fracture.

Load-deflection curves were recorded by load cell and Physitech output which operated an x-y recorder.

The low strength exhibited by the composites containing 15 percent resin led to a decision to use enough resin to fill the void space completely (see Table 5). Void filling required about 30 percent resin based on aggregate weight. Beam tests were conducted in the same manner as previously. The strength observed was greater than that of the partially filled beams (Table 5).

*Flexural strengths are provided as modulus of rupture values. But the modulus of rupture values for the 15 percent resin and fiberglass tests should not be used to compute moment capacities for cross sections other than the tested 6-inch (152-mm) depths. Modulus of rupture values are based on homogeneous materials and the 15 percent resin and fiberglass systems are distinctly nonhomogeneous composites.

A third series of tests was performed in which two layers of woven roving fiberglass (18 oz per sq yd [2.07 kg/m^2]) were placed in the bottom of the mold before adding the aggregate. The beams were made with 15 percent and 30 percent resin. In these tests a significant increase in strength and stiffness was obtained (Table 5).

Following the studies of strength attainment at room temperature, a fourth group of beam test specimens was made and evaluated. These tests were limited to the most promising polyester resin system, LAMINAC 4128. In this series the resin was conditioned to about 54°F (12°C), and both wet and dry aggregates were conditioned to about 32°F (0°C). Thirty percent by weight of polyester resin was used to fill the voids in all specimens. Beams were made with and without fiberglass at the lower face. Specimens were tested at 1/2, 1, and 2 hours after resin application (Table 5). The beam without fiberglass and containing the wet aggregate was the weakest (the ultimate load was less than 25 psi [172 kPa] at 30 minutes) and the beam with fiberglass and dry aggregate was the strongest (able to sustain an ultimate load of more than 868 psi [5.9 MPa] kg at 30 minutes).

In the beam tests all resins except the polyurethane (HASTINGS 1600-1A) displaced free water by floating it to the top. The polyurethane reacted with the water.

In most cases the heat of exotherm was generally high enough to cause the water to evaporate readily. When the total void space was filled with free water, however, little tendency to displace the water was noticed. The highly exothermic materials, particularly the polyesters, showed some thermal cracking after complete reaction had occurred. The cracks seemed to occur only at the surface and were most prominent where the resin was present in thick sections. There was little evidence of thermal cracking within the mass of the beams.

Figures 10 through 21 show typical test beams in various stages of preparation and testing. Figure 22 shows the ultimate load and modulus of rupture versus time after resin application; the ultimate load and modulus of rupture deflection plots indicate stiffness versus time.

Using the CERF analysis model (infinite plate on an elastic foundation), (Reference 1) and a design subgrade modulus of 100 psi (689 kPa) as specified in the Statement of Work, the two aircraft-weight and wheel-loading factors give maximum flexural stress and pavement thickness relationships as shown by the two curves in Figure 23. Adding the 1.5 safety factor in compliance with the CERF study and the maximum allowable pavement thickness (12 in. [305 mm]), the minimum flexural strength of the patch material must be 477 psi (3.29 MPa) for the F-4 loading and 627 for the F-111. From Table 5, it is noted that the LAMINAC 4128 system with fiberglass met the strength requirements in a 30 minute cure time at both cure temperatures when the aggregate was dry. The LAMINAC 4128 fiberglass system with wet aggregates met the F-4 loading criteria in 20 minutes for the 70°F (21°C) tests, and in 45 minutes for the $52^{\circ}\text{F}/32^{\circ}\text{F}$ ($11^{\circ}\text{C}/0^{\circ}\text{C}$) tests; the F-111 loading criteria were met with wet aggregate in 60 minutes for the 70°F (21°C) tests, and in 120 minutes for the $52^{\circ}\text{F}/32^{\circ}\text{F}$ ($11^{\circ}\text{C}/0^{\circ}\text{C}$) tests. Thus, only under dry aggregate conditions and by using fiberglass does the LAMINAC system meet the 30 minute loading criteria specified in the Statement of Work.

Several simplifications and assumptions were made in the above analysis. For one, the LAMINAC-fiberglass system is a nonhomogeneous composite, thus moment capacities for cross sections other than the tested 6-inch (152-mm) depth cannot be predicted accurately using simple flexural criteria.* Conversely, though, if the quantity of fiberglass roving is increased with increasing pavement thickness, it can be assumed that a composite of the same materials can be developed to meet the increased moment capacity modeled from the simple flexural criteria. The modulus elasticity (E) and Poisson's ratios (v) used in Figure 23 are assumed values, but the infinite plate on elastic foundation equation is reasonably insensitive to small changes in these values. Also the infinite plate on elastic foundation ignores the edge influence of the undamaged paving material around the patch, but the simplification is normally conservative and decreases with increasing patch size.

In summary, the flexural tests indicate that the LAMINAC-fiberglass system is an acceptable rapid patching system and appears to meet the strength criteria specified in the Statement of Work if aggregate conditions are dry; under wet aggregate conditions, however, further refinements are needed.

* Simple flexural criteria are given by:

$$f_r \frac{MC}{I}$$

where f_r = extreme fiber stress (modulus of rupture)

M = applied moment

$\frac{I}{C}$ = section modulus

TABLE 5. ACCEPTABILITY OF RESIN CURE/STRENGTH ATTAINMENT RATE

Resin System	Aggregate Moisture	Reinforcement	Ambient Resin Agg.	Resin	Temperature						Modulus of Rupture f_r (psi)* at Given Times From Resin Application to Test (minutes)						
					20	30	45	60	120	180	20	30	45	60	120	180	
HASTINGS 1600-1A	(M)				70°F	70°F	70°F	15	-	-	-	-	-	39	44	-	
HASTINGS 1600-1A	(D)				70°F	70°F	70°F	15	-	-	-	-	-	162	-	283	
EPIREZ 50727/EPICURE 874	(M)				70°F	70°F	70°F	15	-	-	-	-	-	8	64	-	
EPIREZ 50727/EPICURE 874	(D)				70°F	70°F	70°F	15	-	-	-	-	-	67	142	-	
Polyproducts 20-100/21-116	(D)				70°F	70°F	70°F	15	-	-	-	-	-	100	-	-	
EPICAST 530	(D)				70°F	70°F	70°F	15	-	-	-	-	-	-	110	201	-
LAMINAC 4128	(M)				70°F	70°F	70°F	15	-	-	-	-	-	-	812	114	959
LAMINAC 4128	(D)				70°F	70°F	70°F	15	-	-	-	-	-	4	62	125	-
LAMINAC 4128	(D)	Fiberglass			70°F	70°F	70°F	15	228	-	-	-	-	353	-	460	-
LAMINAC 4128	(D)	Fiberglass			70°F	70°F	70°F	15	578	-	-	-	-	646	-	619	-
LAMINAC 4128	(M)	Fiberglass			70°F	70°F	70°F	30	589	-	-	-	-	644	-	723	-
LAMINAC 4128	(D)	Fiberglass			70°F	70°F	70°F	30	333	-	-	-	-	815	-	1507	1275
LAMINAC 4128	(D)	Fiberglass			70°F	70°F	70°F	30	864	-	-	-	-	1523	-	1617	-
LAMINAC 4128	(M)	Fiberglass			52°F	32°F	30	25	-	-	-	-	-	126	-	495	-
LAMINAC 4128	(M)	Fiberglass			52°F	32°F	30	99	-	-	-	-	-	522	-	729	-
LAMINAC 4128	(D)	Fiberglass			52°F	32°F	30	136	-	-	-	-	-	679	-	807	-
LAMINAC 4128	(D)	Fiberglass			52°F	32°F	30	368	-	-	-	-	-	1504	-	1268	-

=Acceptable within strength criteria stated for F-4 ($f_r = 477$ psi)

 =Unacceptable within strength criteria stated for F-11 and F-4 ($f_r = 627$ psi)

Unmarked Samples: resin and aggregate both at 21°C.

*To convert psi to Pa, multiply the psi value by 6894.757.

SECTION V

FIELD DEMONSTRATIONS OF SELECTED SYSTEMS FOR REPAIR OF DAMAGED PAVEMENTS

GENERAL

Three of the most favorable resin systems were selected for use in repair demonstrations set up by AFCEC and the Waterways Experiment Station (WES) at WES. The selected resin systems were: HASTINGS 1600-1A, POLYPRODUCTS 20-100/21-116, and LAMINAC 4128.

Repair patches of three different diameters were made: the smallest was about 2 feet (0.6 meter) in diameter and 1 foot (0.3 meter) deep; the intermediate size was 5 feet (1.6 meters) in diameter and 2 feet (0.6 meter) deep; and the largest was 8 feet (2.6 meters) in diameter and 2.5 feet (0.75 meter) deep. All craters were prepared by cutting circular holes through a flexible pavement test pad into the subgrade material. The flexible pavement was about 8 inches (0.2 meter) thick and on an undetermined subgrade modulus. Figures 24 through 26 show the demonstration craters.

POLYURETHANE RESIN

The first material tested was HASTINGS 1600-1A, a polyurethane resin. A small crater and an intermediate crater were filled with wet aggregate between 1/2 and 3/4 inches (12 and 19 mm) in diameter. Excess gravel was removed by levelling with a board until the surface of the aggregate was even with the surrounding pavement. Preweighed batches of resin (about 22 lb [10 kg]) were mixed in 5-gal (20-liter) containers by a mechanical stirrer and were poured on top of the aggregate. The amount of resin applied was predetermined to weigh about 15 percent of the weight of the aggregate in the patch. Since the Hastings material was a polyurethane which reacts with water, the repair patch foamed and heaved until the top of the cap was about 6 inches (0.15 meter) higher than the surrounding pavement. A 30,000 pound (13,600 kg) load cart with an aircraft tire inflated to 270 psi (1930 kPa) was run over the cap 30 minutes after resin application. The cap material was very spongy and the aircraft wheel sank to the bottom of the patch repair material in the intermediate-diameter hole. An hour after resin application, however, the undamaged portion of the patch sustained the load cart passage without damage. Figures 27 through 35 show the preparation and testing of the repair patch and the damage. From this test it was concluded that the polyurethane system would not be satisfactory for BDR.

EPOXY RESIN

The second test material was POLYPRODUCTS 20-100/21-116, an epoxy system. The test craters were of small and intermediate size as described for the first test. The amount of resin used was again calculated to be about 15 percent of the aggregate weight used. The aggregate used was cleaner and

drier than had been used during the first test. The test patches were traffic-tested 30 minutes after the application of resin. The epoxy patch sustained passage of the load cart without obvious distress or failure during 100 passes. However, some of the aggregate ravelled from the surface of the repair and some of the pieces that projected above the surface broke off. It was judged that completely filling the void volume in the aggregate with resin would have minimized the release of aggregate. The Polyproducts material performed satisfactorily in the demonstration test. Figures 36 through 40 show the preparation and testing of the epoxy repair patches. The ravelling is shown in Figure 41. The first two tests were conducted in sunny weather at about 75°F (24°C) with slight wind.

POLYESTER RESIN

The third material demonstrated in a field application was LAMINAC 4128, a polyester system. Because of the material's low cost and its performance in the laboratory tests, it was decided to completely fill the aggregate voids with resin using about 30 percent resin by weight of aggregate. This was done both for strength and to see if the ravelling condition could be reduced.

Three repair patches were made: one each in a small and an intermediate crater in which the resin was allowed to permeate the whole aggregate fill (Figures 42 through 46) and one in a large crater. In the latter repair the crater was filled with dry aggregate to within about 6 inches (0.15 meter) below the pavement surface (Figure 47). After levelling this fill, two layers of fiberglass woven roving were placed on top of the fill (Figure 48). Additional dry aggregate was placed on top of the fiberglass and levelled with the pavement surface (Figure 49). Each patch was filled with resin mixed in 35-pound (16-kg) batches and poured on top of the aggregate until the void volume was filled. Excess resin was inadvertently applied to each patch, causing a slight ponding of resin (Figure 50). In all three tests it was impossible to judge when the voids were filled because the fluid pooled on the surface and seeped slowly down. This represents a problem with this approach. Other steps, such as sanding the surface after the resin is applied, might alleviate the problem as well as provide a smoother patch surface.

Thermal cracking occurred on the surface where the ponding caused a resin thickness of about 1/2 inch (12 mm) or greater (Figure 51). The load cart was run over the patches commencing 30 minutes after resin application. Except for minor flaking off of the thermally cracked resin and a very small number of broken aggregate particles (where they projected above the patch surface), the patches all performed well (Figure 52). The small patch rotated within the dish-shaped crater (Figure 53) and it was evident that the exothermic heat had softened the asphaltic binder in the flexible pavement material (Figure 54). Likewise, in the two larger crater repairs, the patch did not bond to the pavement because the asphaltic binder was heat softened and the resin shrank somewhat (Figure 55). Because of the oily nature of asphaltic materials most resins will not bond to them. The shrinkage was about 1/4 inch (6 mm) across the diameter of the patches. There was no obvious deflection of the patch material under load in either the small or intermediate size patches. The large cap deflected approximately 1/8 inch (4 mm) when the load cart was near the center of the cap (Figure 56) but returned to the original

level when the load moved off the cap. Each patch withstood the prescribed 100 passes of the load cart. The large patch was retested some 18 hours after resin application and performed as it had in the earlier test.

A portion of the intermediate patch material was excavated with an air hammer. The resin had penetrated to the bottom of the aggregate and there was no evidence of thermal cracking within the mass of the resin concrete.

The test repairs described above were made when the aggregate and resin temperatures were considerably lower than during the earlier tests. The small and intermediate patches were made when the temperature was 40°F (5°C) and the large repair cap was made when the temperature was about 52°F (11°C).

Within the temperature range of potential applications, it would be necessary to adjust the amount of catalyst added to the resin in order to regulate the gel and cure times. About 0.5 percent catalyst is required at 125°F (52°C), and about 1.5 percent is required at 35°F (2°C). Machine application would allow adjustment by dial setting; hand mix application could be by temperature-volume of catalyst relation curve charts provided with the material.

In summary, the field tests have proven that the LAMINAC fiberglass system is a field-placeable system with the surface stability to withstand 100 passes of a single wheel 30,000 pounds (12 000 kg)/load at 270 psi tire pressure. The tests did indicate the need for further investigation of thermal cracking caused by surface ponding of the resin and the bonding of the resin patch to asphalt pavements.

SECTION VI

IDENTIFICATION OF THE MOST PROMISING MATERIAL

Polyesters were the most promising family of resins investigated. The most suitable polyester evaluated was LAMINAC 4128, which meets the requirements of US Air Force Specification MIL-R-7575B, GRADE A, Class 1. The resin is usually used for compression molding of parts that require good heat strength. Fuel tanks for aircraft are also molded from this resin.

LAMINAC 4128 can be catalyzed by methyl ethyl ketone peroxide promoted by cobalt naphthanate. Gelling and curing times can be varied by adjusting the proportions of catalyst to promoter. For best performance the resin components should be maintained above 32° F (0° C). Short-term exposure to temperatures ranging from -22° F to 122° F (-6° C to 50° C) does not affect the subsequent performance of the resin. The material is easily mixed by hand or machine.

When applied to selected aggregate that is within the range of -22° F to 122° F (-6° C to 50° C), the resin gels and cures rapidly (it has been maintained at 50° F [10° C]), forming a strong, rigid composite that can be designed into repair patches that are trafficable in 30 minutes or less.

The LAMINAC 4128 resin and other resins with similar properties are readily available in bulk quantities. The cost is about \$.60 per pound (\$1.32/kg), the lowest of any resin system evaluated. The low cost makes it possible to completely fill the void volume in the aggregate within the cost restraints specified.

Table 6 lists the 15 objectives of the study and discusses the performance of LAMINAC 4128 polyester resin with respect to each objective.

Tables 2 and 5 and previous discussion give the reasons other resin systems were considered inappropriate for BDR.

TABLE 6. LAMINAC 4128 PERFORMANCE WITH REGARDS TO OBJECTIVES CRITERIA

1. REQUIREMENT: Application of the resin to the aggregate and cure to load-carrying capacity must be within 30 minutes for all temperatures between 35°F (2°C) and 125°F (51°C). The aggregate temperature will be the same as ambient temperature.

PERFORMANCE: Flexural beam tests on the LAMINAC system have demonstrated the potential of achieving the 30-minute cure to load carrying capacity. To meet this strength-time requirement at the lower end of the temperature range the beams were reinforced with two layers of fiberglass roving, the aggregates were dry, and the resin temperature prior to placement was 52°F (11°C).

2. REQUIREMENT: The resin concrete repair patch must sustain the launch of 50 tactical aircraft without repair. The design aircraft for the repair will be the F-4 (30 kip load at 265 psi) and the F-111 (50 kip load at 150 psi). The design subgrade will have a modulus of subgrade reaction (k) of 100 pounds/in³ or a California Bearing Ratio (CBR) of 3.

PERFORMANCE: The field test demonstrated the surface stability of the LAMINAC system to withstand 100 passes of a 30,000-pound (13 MPa) load cart (270 psi [1.86 MPa] tire pressure). The flexural tests and related model analysis with the 1.5 safety factor indicate that a 12-inch (0.3-meter)-thick LAMINAC-fiberglass system can be fabricated to meet the F-4 and F-111 load criteria and time/temperature requirements, if the dry aggregate and resin temperature restrictions are adhered to.

3. REQUIREMENT: The aggregate quality requirements may not exceed ASTM C33-71, "Standard Specifications for Concrete Aggregate."

PERFORMANCE: With the exception of the single-size aggregate gradation restriction, the required aggregate quality did not exceed the requirements of ASTM C33-71, "Standard Specifications for Concrete Aggregate."

4. REQUIREMENT: The repair cap will not exceed 1 foot (.3 meter) in thickness.

PERFORMANCE: See performance discussion for requirements 1 and 2.

5. REQUIREMENT: The resin concrete must use the minimum amount of resin possible, preferably no more than 15 percent by weight of aggregate.

PERFORMANCE: The flexural strength of the 15 percent LAMINAC aggregate system was very low, especially under wet aggregate conditions. The addition of the fiberglass roving to the 15 percent resin samples did significantly increase the early strength (578 psi) (4 MPa) at the 76°F (21°C) temperature and dry aggregate conditions, but the best results were achieved at the lower temperatures with the 30 percent resin system. Also, the field tests indicated that the 15 percent resin

TABLE 6. LAMINAC 4128 PERFORMANCE WITH REGARDS TO OBJECTIVES CRITERIA
(CONTINUED)

system did tend to ravel during the 100 passes of the load cart. The relative low cost of the LAMINAC 4128 resin allows the 30 percent resin system to remain within the cost restraints (Requirement No. 15).

6. REQUIREMENT: The aggregate will be placed by dumping from dump trucks, spread by front-end loaders and dozers, and graded by a grader. No compaction will be done.

PERFORMANCE: This procedure worked satisfactorily in the field trials.

7. REQUIREMENT: The liquid resin must be able to be both equipment mixed and sprayed and mixed and poured by hand upon the aggregate. When the resin is sprayed, both application and cure must be within 30 minutes. When the resin is poured by hand upon the aggregate, only the cure, after pouring, must be within 30 minutes.

PERFORMANCE: Flexural beam specimens and the field-trial patches were both prepared by hand mixing the LAMINAC 4128 resin. Similar materials are easily mixed by equipment including spraying equipment. Tests showed the cure of LAMINAC 4128 to be adequate after 30 minutes to allow the composite to accept the design load. But the field tests did indicate a minor problem with thermal cracking of excess resin that had ponded on the surface of the patch. The ponding was caused by the slow seepage of the resin into the aggregate voids.

8. REQUIREMENT: The liquid resin must have a kinematic viscosity (ASTM D2170) between 40 and 120 centistokes for all temperatures between 35°F (2°C) and 125°F (51°C) to allow for spraying over the aggregate.

PERFORMANCE: LAMINAC 4128 has a viscosity of about 10,000 centipoise (mPa.s) at room temperature. It is near 15,000 centipoise (mPa.s) at 32°F (0°C) and at this viscosity was found to flow down through the 1/2- to 3/4-inch (12- to 19-mm) aggregate. Though, as indicated above, the resin did seep through the aggregate so slowly that it was impossible to determine the exact amount of resin required to just fill the voids; thus some ponding of resin occurred.

9. REQUIREMENT: The resin must be able to displace free water in the aggregate, bond to wet aggregate, and cure to load carrying capacity within 30 minutes.

PERFORMANCE: LAMINAC 4128 has a specific gravity of 1.13 and will displace free water. This was noted in some of the flexural beam preparations. It does not bond well to wet aggregate (very few resins will). There are methods for increasing the bond strength to wet aggregate, but these were beyond the scope of this study. When in contact with wet aggregate LAMINAC will cure to load-carrying capacity within 30 minutes provided the void space is completely filled and fiberglass is used at the bottom face of the beam or patch.

TABLE 6. LAMINAC 4128 PERFORMANCE WITH REGARDS TO OBJECTIVES CRITERIA
(CONTINUED)

10. REQUIREMENT: All major components of the resin must have a minimum shelf life of 3 years at 72°F (22°C). All minor components must have a minimum shelf life of 1 year at 72°F (22°C). The major component is any material comprising 15 percent or more by weight or volume of the total mix of the resin and its components. Both major and minor components must be able to tolerate exposure to extremes (0° to 125°F [-18° to 51°C]) for 12 hours without degradation.

PERFORMANCE: Unpromoted, uncatalyzed LAMINAC 4128 can be compounded with inhibitors to extend shelf life to about 5 years. Recent studies have already identified the inhibitor and quencher necessary to accomplish the desired shelf life. Minor components present no problems. Within this study, extreme temperature exposures of 12 hours (actually up to 48 hours) did not degrade the LAMINAC 4128 or affect its subsequent gelling and curing rates.

11. REQUIREMENT: Storing and handling must not present unusual hazards for personnel or the environment.

PERFORMANCE: LAMINAC 4128 (and similar polyester resins) have a long history of use and have not shown unusual hazards or the potential for unusual hazards.

12. REQUIREMENT: The cured resin concrete must be nonflammable and insusceptible to attack by petroleum products.

PERFORMANCE: LAMINAC 4128 will burn slowly if a flame is held to it. A highly filled material, such as BDR patch, reduces the burnability to near nonexistence. LAMINAC 4128, when cured, is not attacked by petroleum products; it is used in making fuel tanks for some aircraft.

13. REQUIREMENT: The repair patch must retain its serviceability despite natural conditions. Rapid loss of serviceability due to sunlight or freeze-thaw, for example, is unacceptable. Resistance to weathering should be comparable to or better than Portland cement concrete or asphaltic concrete.

PERFORMANCE: Filled polyesters, such as LAMINAC 4128, are resistant to freeze-thaw and sunlight for several months. Complete void filling to exclude free water decreases freeze-thaw damage. Temporary BDR patches made of this material should be serviceable for a long time but will probably not be more weather resistant than PC concrete or asphaltic concrete.

14. REQUIREMENT: The repair patch must be able to be repaired by addition of extra aggregate and resin.

TABLE 6. LAMINAC 4128 PERFORMANCE WITH REGARDS TO OBJECTIVES CRITERIA
(CONCLUDED)

PERFORMANCE: Repair procedures, if repair is necessary, are the same as for forming the initial resin concrete patch. The same materials will provide for effective repair of the patch itself.

15. REQUIREMENT: The cost of the resin and its components will not exceed \$20 per square foot of repair.

PERFORMANCE: LAMINAC 4128 costs about \$.60 per pound (\$1.32/kg) and even when applied at 30 percent by weight of aggregate (complete void filling) in a 12-inch (0.3 meter) thick patch it costs \$20 per square foot (\$215 per square meter). For lesser thickness, obviously the cost is lower than the \$20 per square foot (\$215 per square meter) requirement.

SECTION VII

CONCLUSIONS

This study met most, but not all, of the objectives in the Statement of Work from AFCEC. The following is a list of the most pertinent findings.

1. Several highly reactive, highly exothermic resins fall within the desired application viscosities (less than 15,000 centipoise) and meet the 30 minute gel requirement over the 35 to 120°F (2 to 49°C) temperature range.
2. A 12-inch (0.3-meter)-thick resin concrete system consisting of 30 percent polyester resin (LAMINAC 4128), dry 1/2- to 3/4-inch (12- to 19-mm) aggregate, and reinforced on the bottom face with fiberglass roving, theoretically meets the requirements of 30-minute cure time and 35 to 120°F (2 to 49°C) temperature range for the F-4 and F-111 design loads if the resin is maintained at 50°F (10°C) or higher. The material cost of the fiberglass-reinforced resin system is less than the \$20 per square foot (\$215 per square meter) allowed for in the 12-inch (0.3-meter)-thick patch.
3. Field tests have confirmed the field placeability and surface stability under repetitive loadings of the polyester-fiberglass patching system. The polyester patches did not bond to the asphalt paving materials because the exothermic heat softens the asphalt in the pavement and the resin matrix shrinks upon cooling. Also, the field tests indicated that due to the slow seepage of the resin through the aggregate, it is easy to apply excess resin which ponds on the patch surface after all voids have been filled. These "ponds" tend to thermally crack during curing. The cracks do not appear to penetrate much below the surface.
4. The polyester-fiberglass system (and other resin systems) are sensitive to free moisture on the aggregate surface. Surface moisture hinders the aggregate-resin bond and the resulting flexural strength. Laboratory tests with wet aggregate meet the F-4 and F-111 design loads, but not in the 30-minute required cure time under the low temperature test conditions (aggregate 35°F [2°C] and resin 51°F [10°C]).

SECTION VIII

RECOMMENDATIONS

Based on the results of this study, which indicate the probability of successfully preparing a resin concrete repair cap, CERL recommends that the second phase of the BDR study, conceptual equipment design, be initiated. Since some of the Statement of Work objectives were not completely satisfied, however, it is recommended that further material studies be continued on the polyester patching system. These studies should emphasize improving the bonding characteristics of the resin to wet aggregate, enhancing the long term storage stability of the resin, decreasing the resin viscosity, and developing the material data required to accurately design a fiberglass-reinforced patch. Concurrently, more rigorous design and analysis procedures should be used in designing the polyester patching system. The sponsoring agency has decided not to continue this study, but suggests that new concepts be investigated.

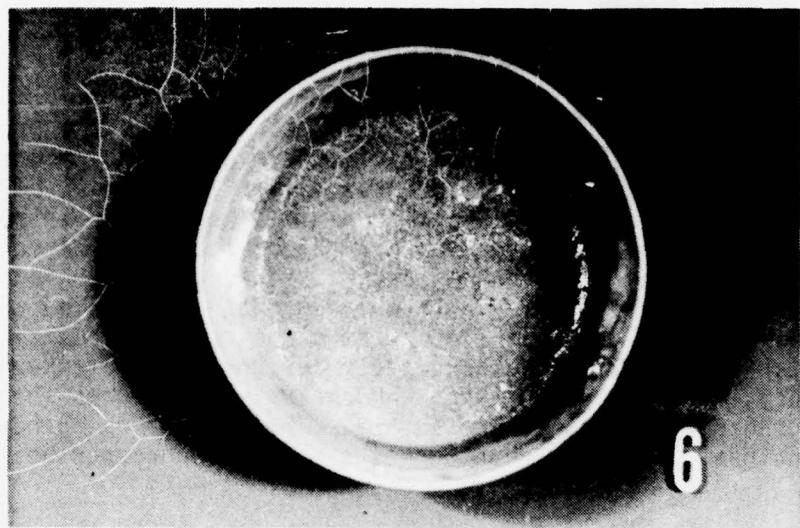


Figure 1. 100 gm Neat Resin Batch

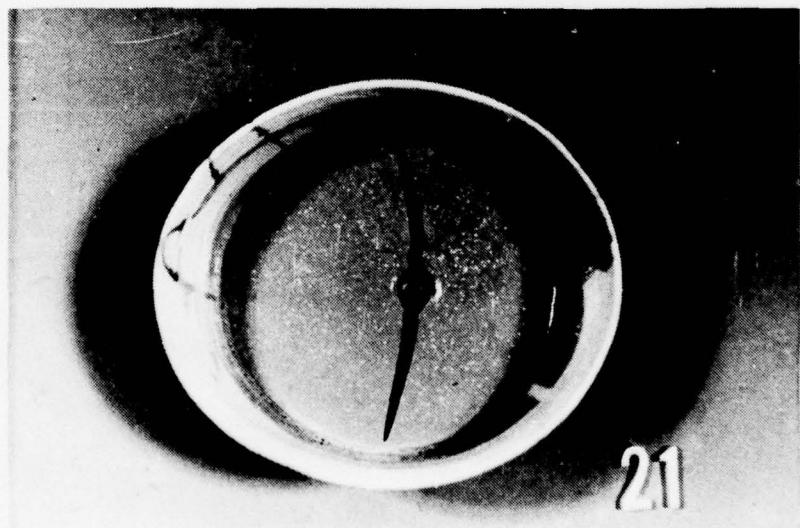


Figure 2. Thermal Crack in Neat Epoxy Resin

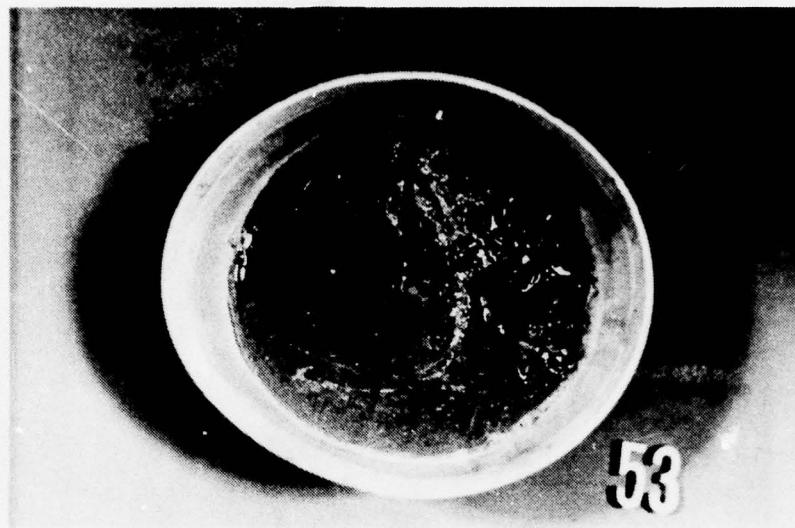


Figure 3. Thermal Crack in Neat Polyester Resin

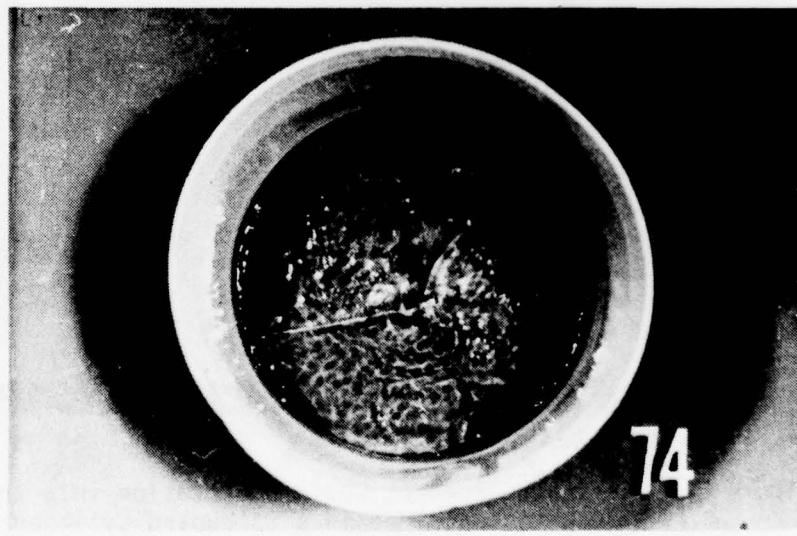


Figure 4. Thermal Crack in Neat Resin



Figure 5. Application of Resin to Aggregate

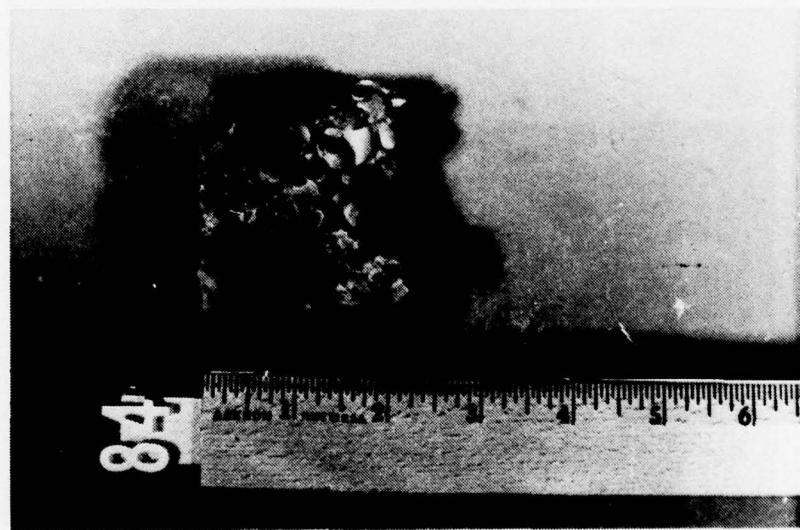


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder

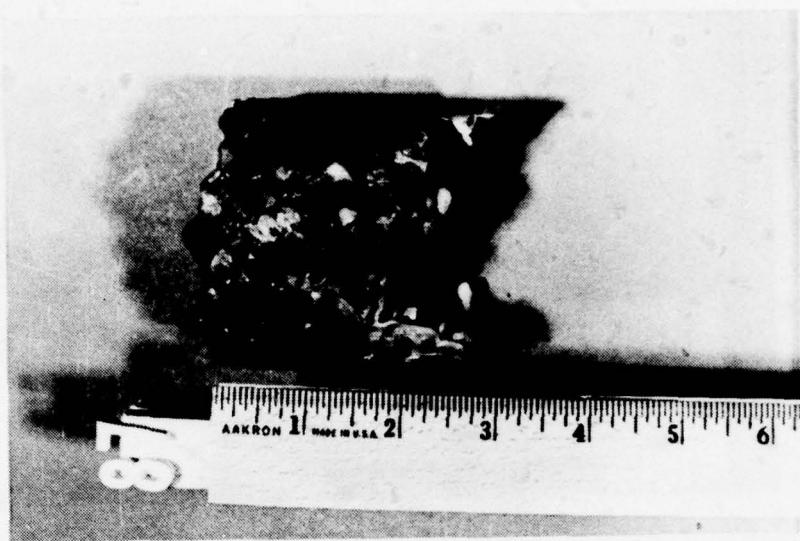


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder (Continued)

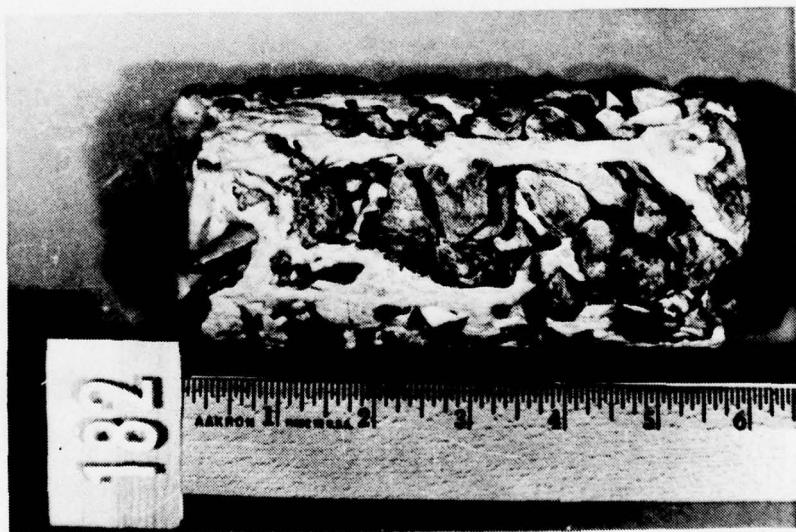


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder (Continued)

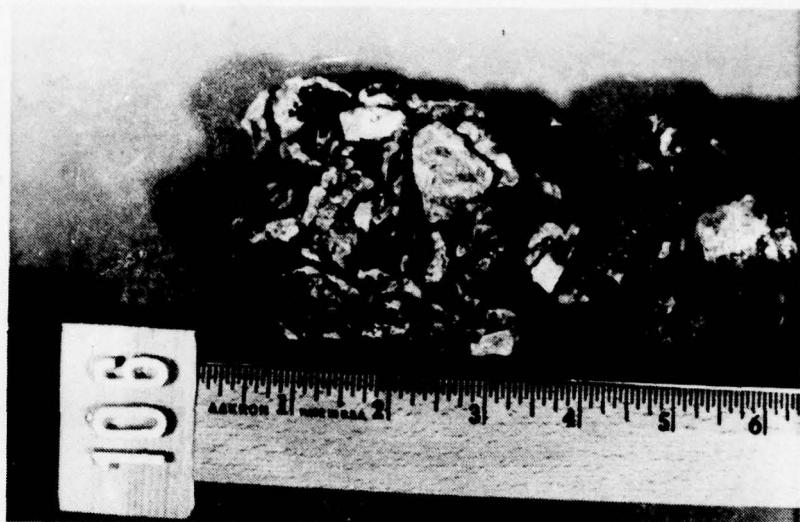


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder (Continued)

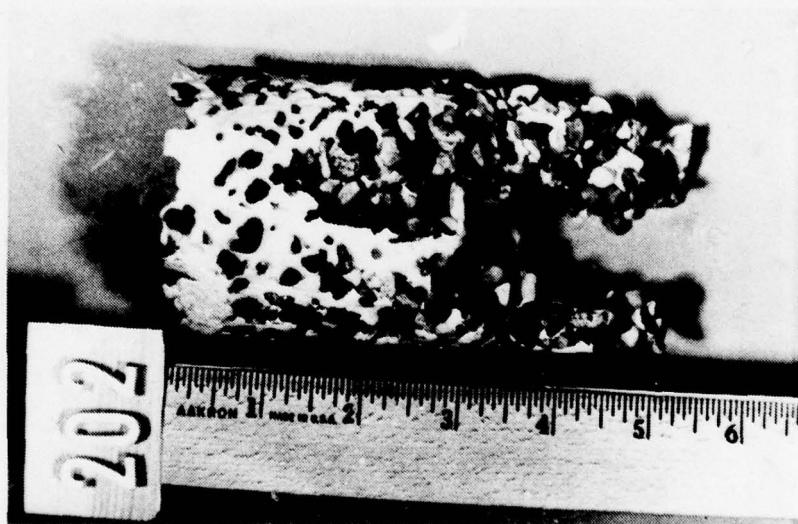


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder (Continued)

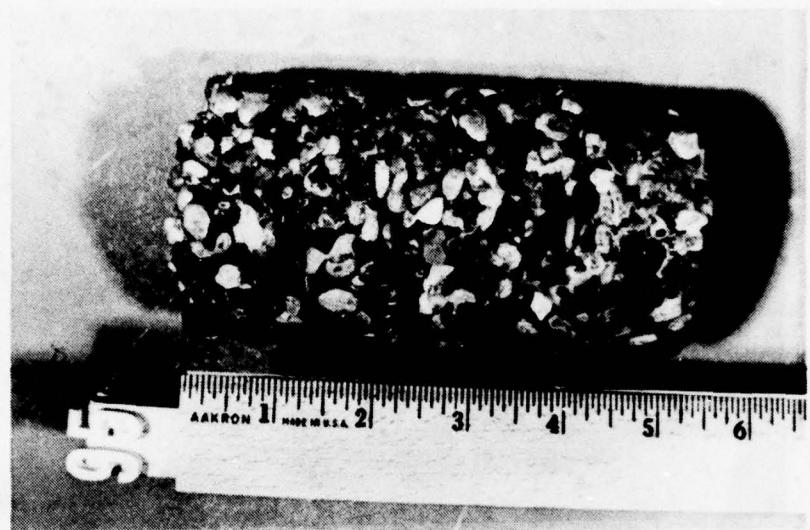


Figure 6. Varying Degrees of Resin Penetration into the Aggregate Contained in a Cardboard Cylinder (Concluded)

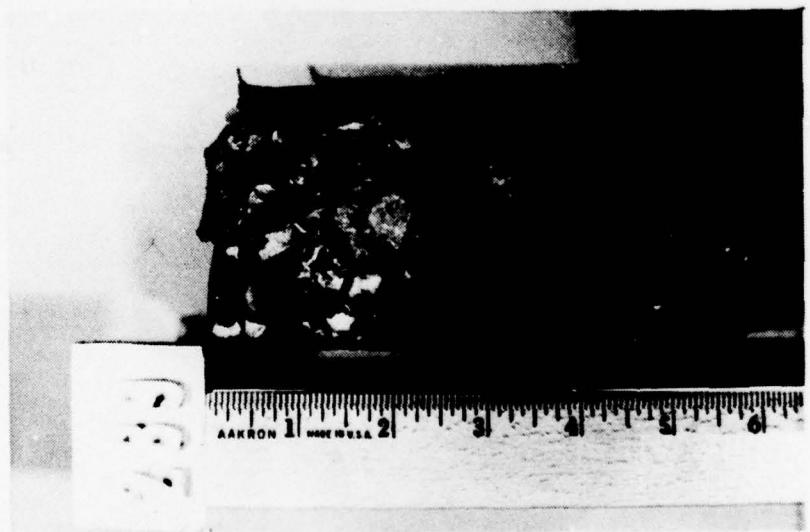


Figure 7. Foaming of Polyurethane Resin

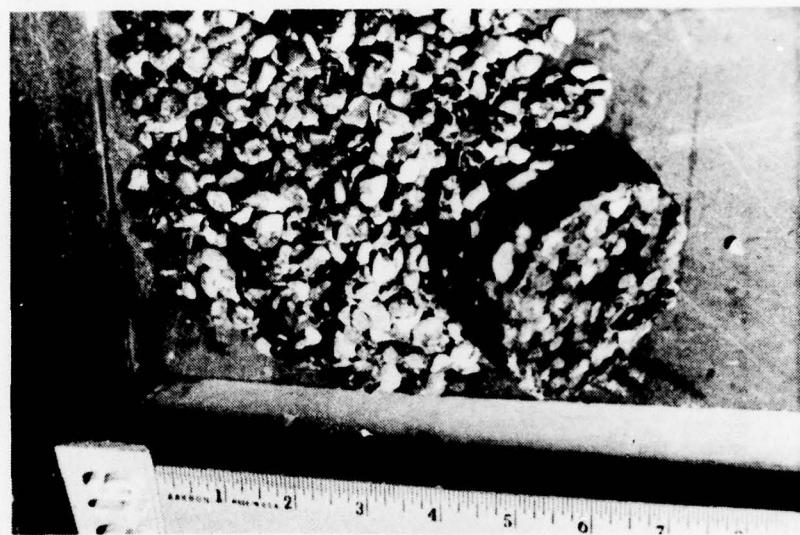


Figure 8. Failure of Dow Epoxy Resin to Cure in Presence of Moisture



Figure 9. Failure of Celanese Epoxy Resin to Cure in Presence of Moisture

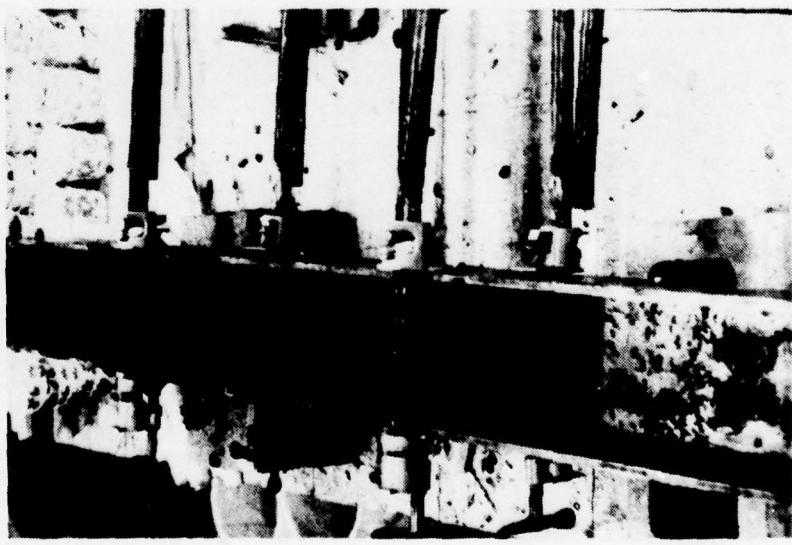


Figure 10. Mold for Making Test Beams

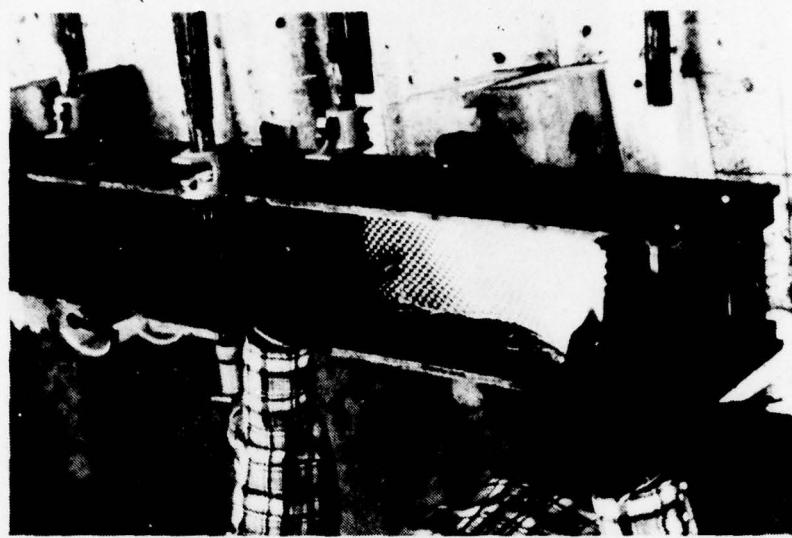


Figure 11. Insertion of Fiberglass Cloth into Mold

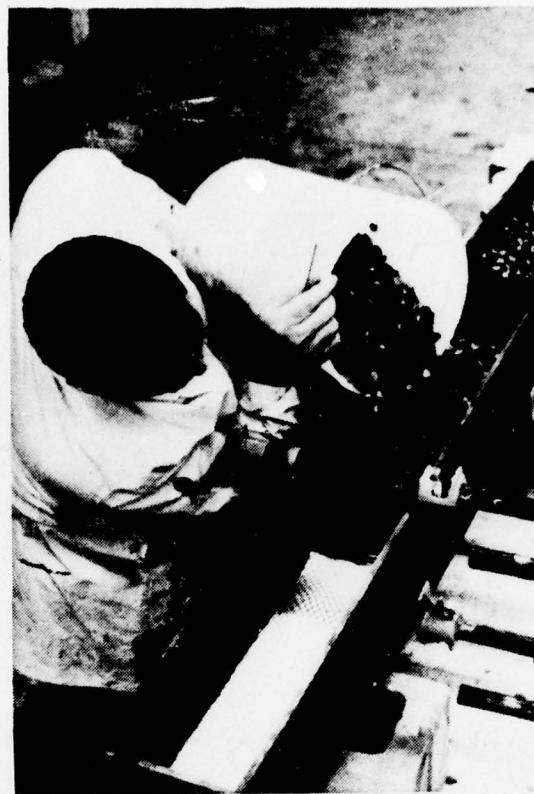


Figure 12. Pouring of Aggregate into Mold



Figure 13. Mixing of Resin

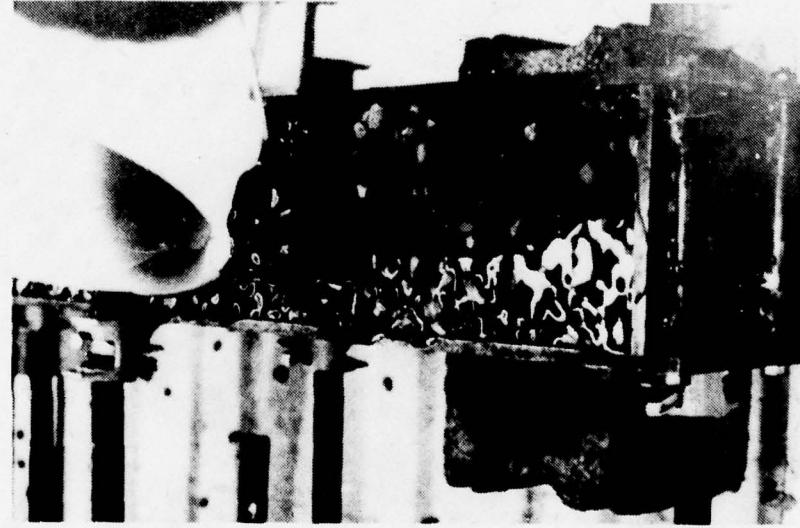


Figure 14. Application of Resin to Make Test Beam

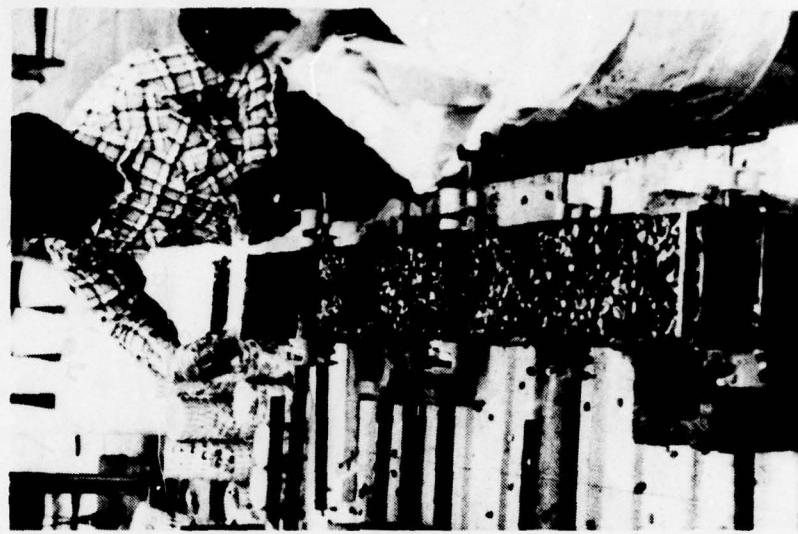


Figure 15. Preparation of Resin to Make Test Beam

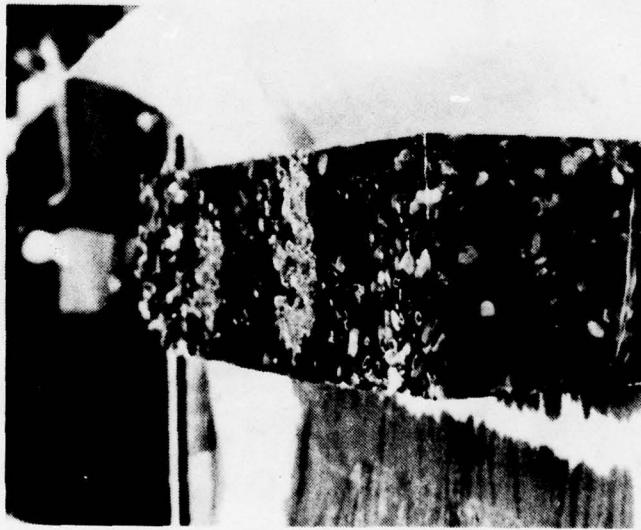


Figure 16. Completed Test Beam



Figure 17. Making Load Points on Beam

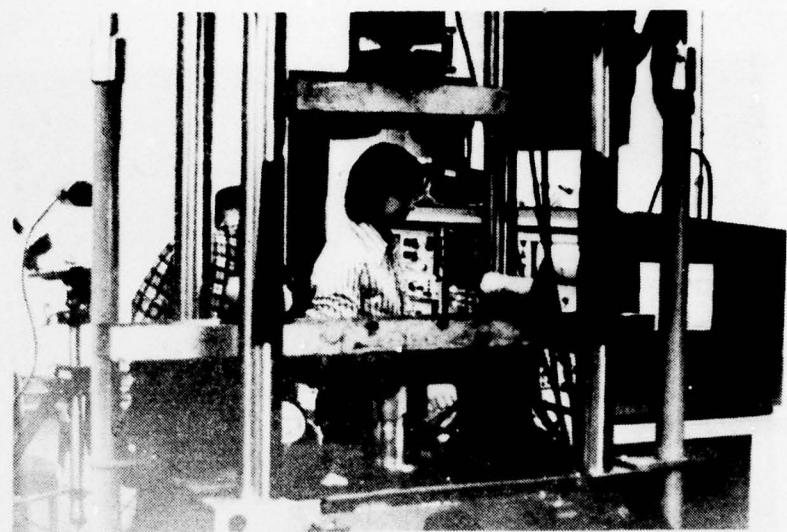


Figure 18. Flexural Test Equipment

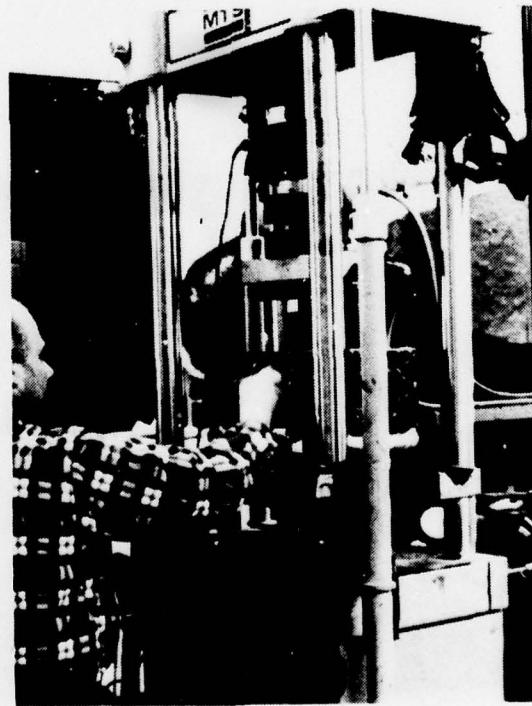


Figure 19. Beam in Test Fixture

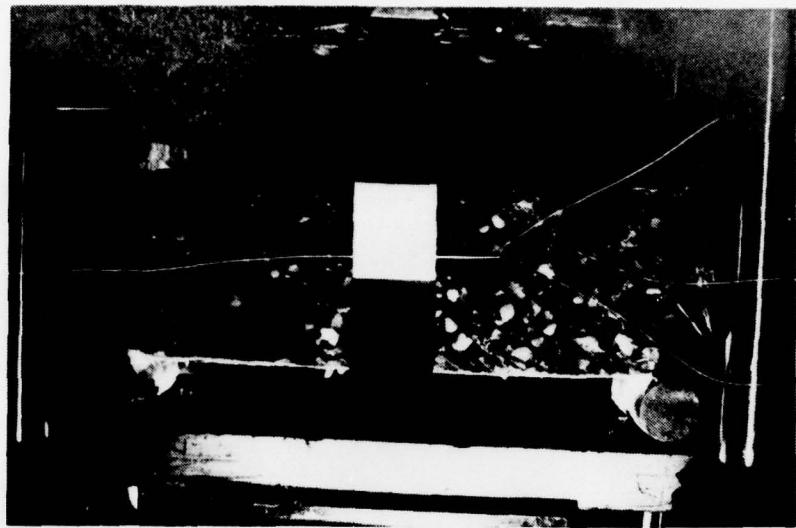


Figure 20. Optical Target Affixed to Beam

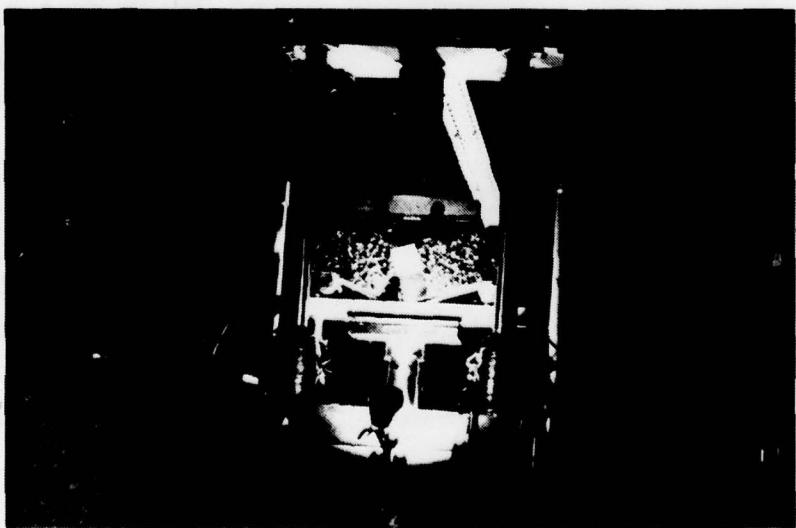
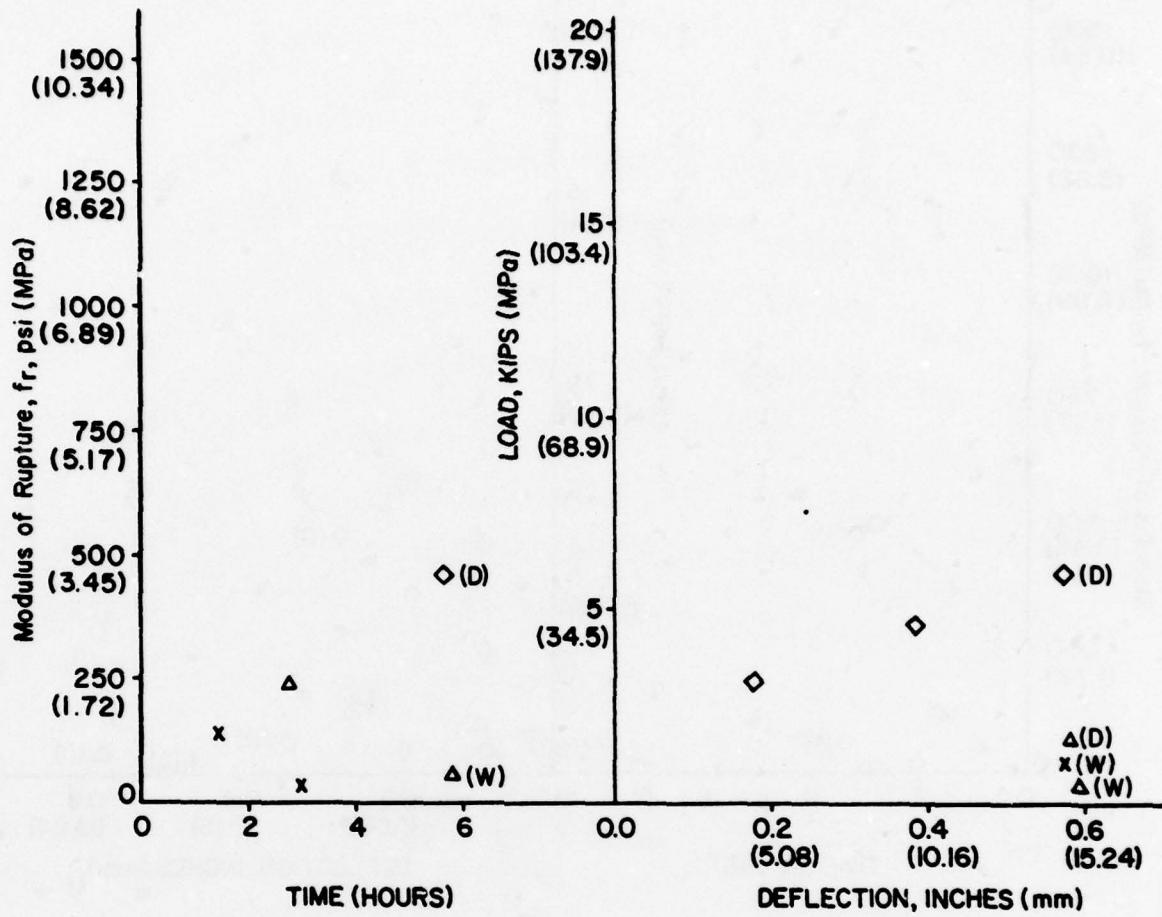


Figure 21. Beam After Failure



LEGEND

✗ = EARLIEST TEST

△ = INTERMEDIATE TEST

◇ = LATEST TEST

PRODUCT: HASTINGS 1600-1A

PERCENT BY WEIGHT OF AGGREGATE: 15

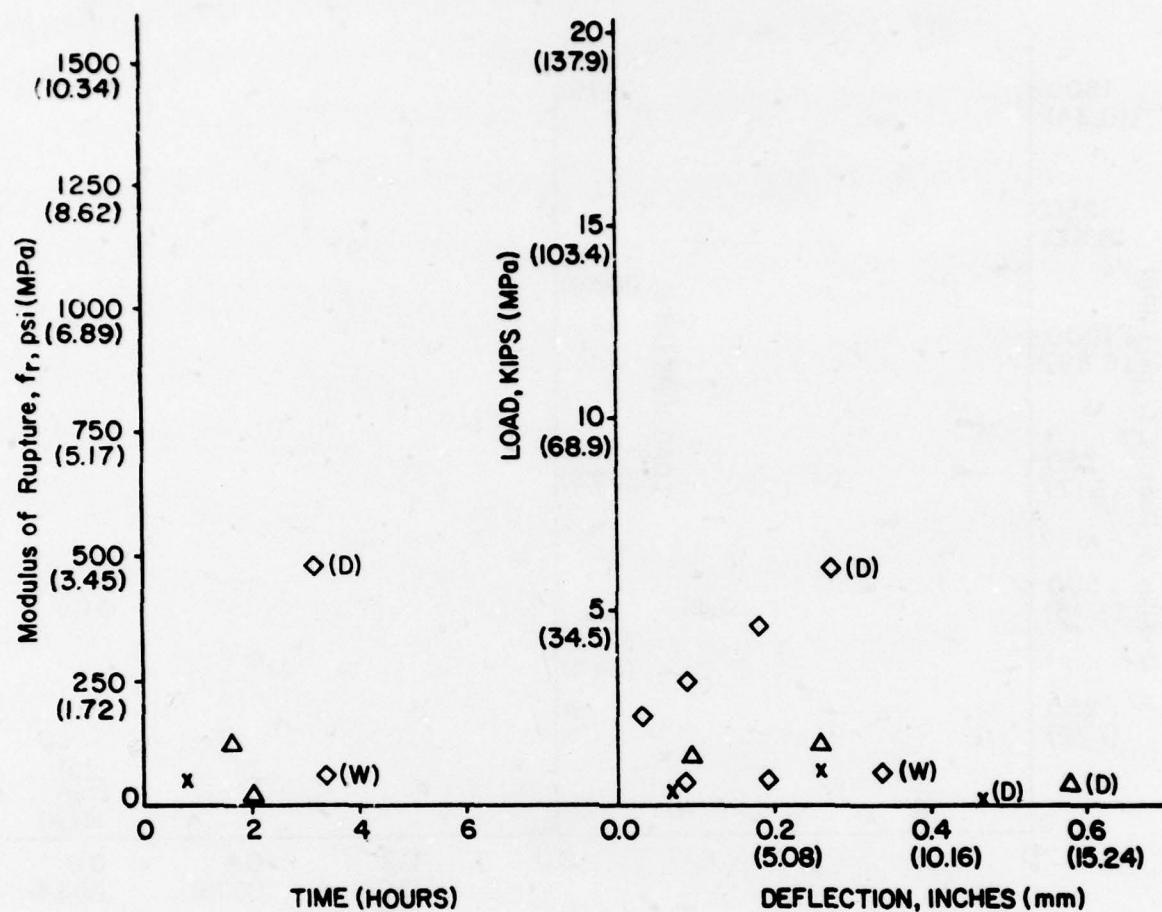
CONDITION OF AGGREGATE: W = WET, D = DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ\text{C}$

PLAIN

REMARKS: ONLY TWO TESTS WERE RUN BECAUSE
OF THE VERY SLOW CURE RATE.

Figure 22. Flexural Strength Test Results



LEGEND

- × = EARLIEST TEST
- △ = INTERMEDIATE TEST
- ◊ = LATEST TEST

PRODUCT: CELANESE EPIREZ 50727/EPICURE 874

PERCENT BY WEIGHT OF AGGREGATE: 15

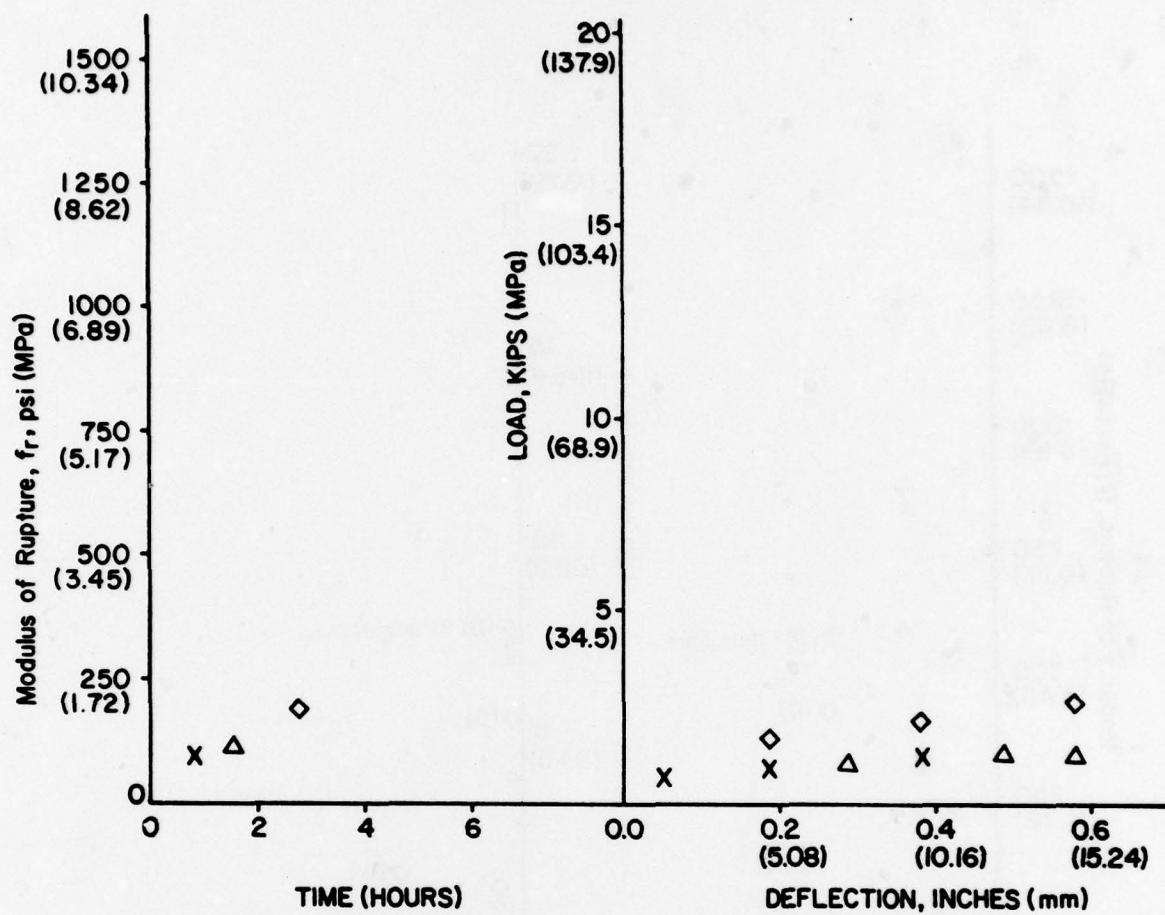
CONDITION OF AGGREGATE: W = WET, D = DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ\text{C}$

PLAIN

REMARKS: FIRST BEAM FAILED WHILE BEING CARRIED
TO TEST SETUP.

Figure 22. Flexural Strength Test Results (Continued)



LEGEND

- ✗ = EARLIEST TEST
- △ = INTERMEDIATE TEST
- ◊ = LATEST TEST

PRODUCT: 20-100/21-116

PERCENT BY WEIGHT OF AGGREGATE: 15

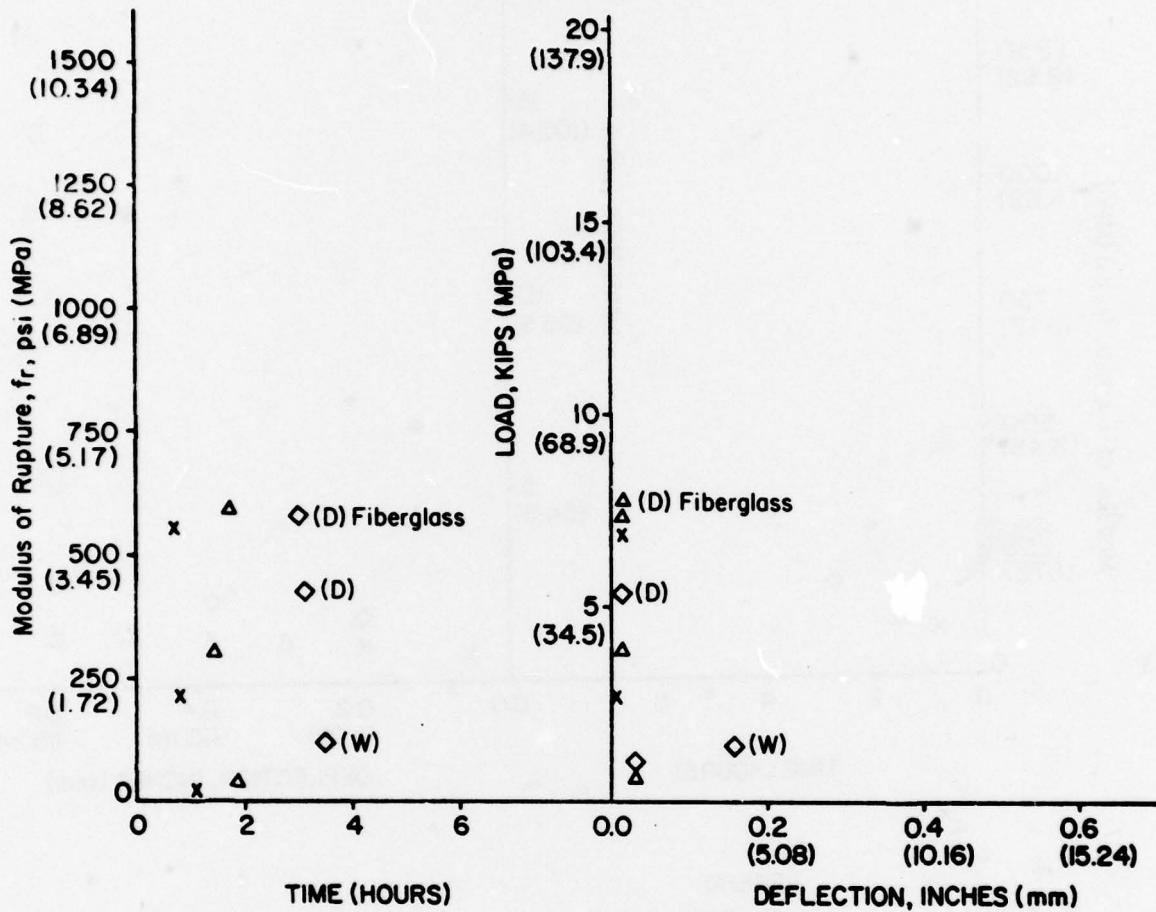
CONDITION OF AGGREGATE: W=WET, D=DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ \text{C}$

PLAIN

REMARKS: BECAUSE OF POOR PERFORMANCE WITH DRY
AGGREGATE, TESTS WERE NOT RUN ON WET
AGGREGATE.

Figure 22. Flexural Strength Test Results (Continued)



LEGEND

- ✗ = EARLIEST TEST
- △ = INTERMEDIATE TEST
- ◇ = LATEST TEST

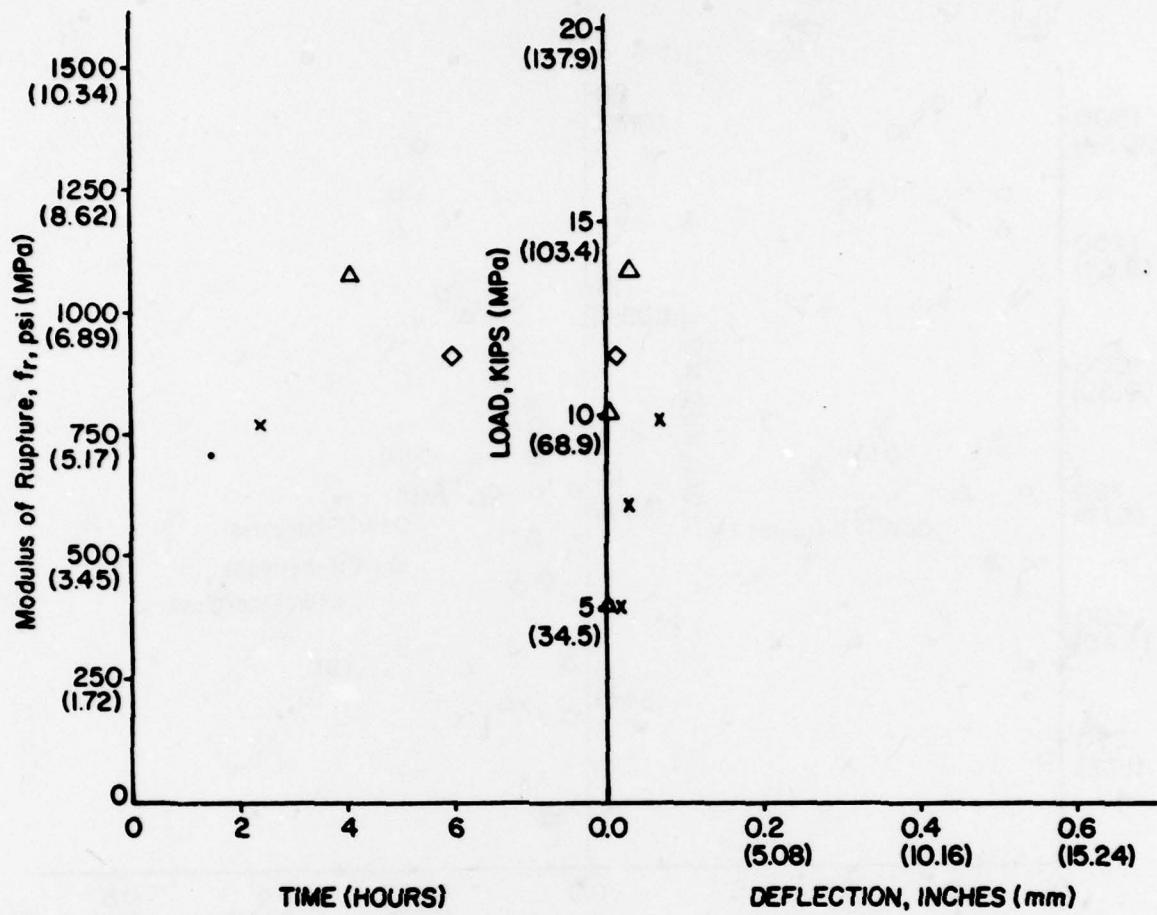
PRODUCT: LAMINAC 4128

PERCENT BY WEIGHT OF AGGREGATE: 15

CONDITION OF AGGREGATE: W = WET, D = DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ\text{C}$

Figure 22. Flexural Strength Test Results (Continued)



LEGEND

- \times = EARLIEST TEST
- Δ = INTERMEDIATE TEST
- \diamond = LATEST TEST

PRODUCT: EPOCAST 530

PERCENT BY WEIGHT OF AGGREGATE: 15

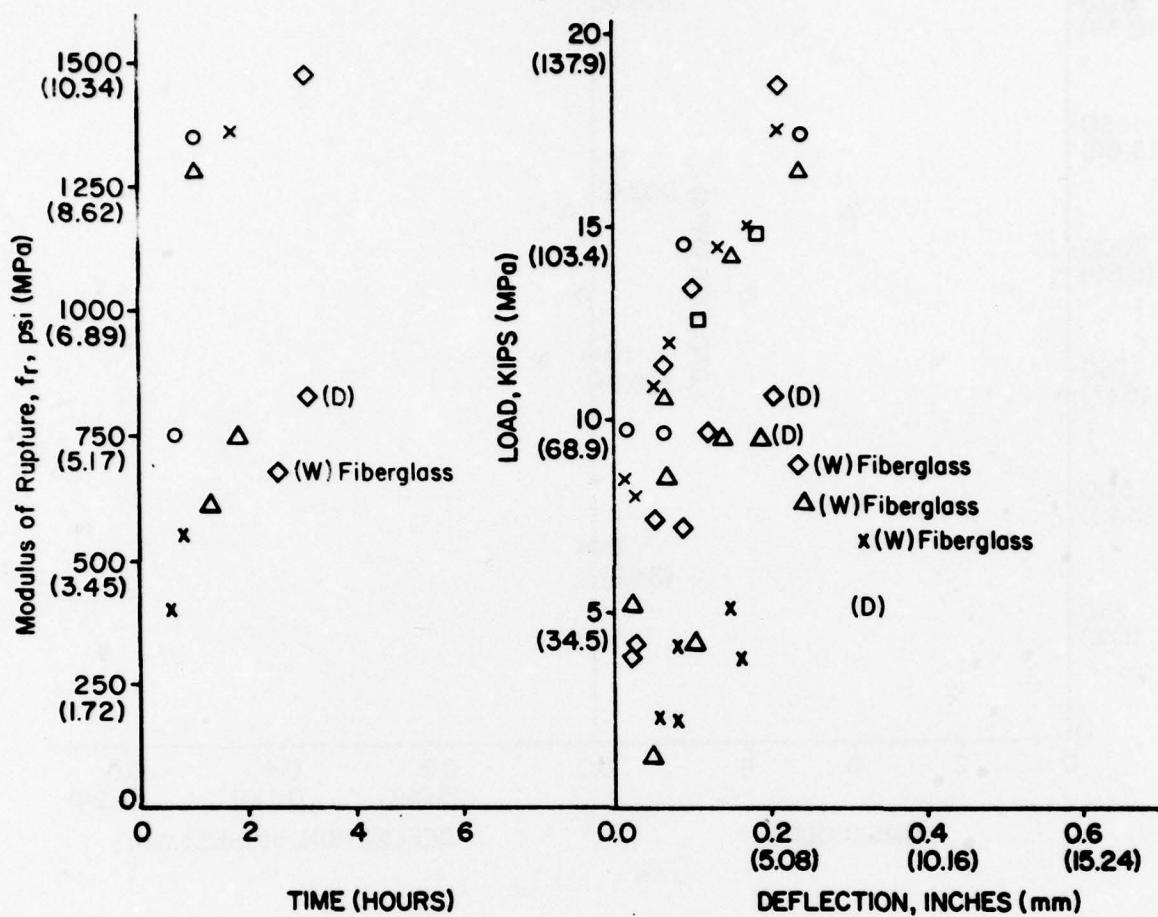
CONDITION OF AGGREGATE: W = WET, D = DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ\text{C}$

PLAIN

REMARKS: RUBBERY FOR OVER 2 HOURS AFTER RESIN
APPLICATION. WET NOT RUN BECAUSE OF
FURTHER RETARDATION OF CURE.

Figure 22. Flexural Strength Test Results (Continued)



LEGEND

◊ = EARLIEST TEST

Δ = INTERMEDIATE TEST

◊ = LATEST TEST

PRODUCT: LAMINAC 4128

PERCENT BY WEIGHT OF AGGREGATE: 30 (VOID VOLUME FILLED)

CONDITION OF AGGREGATE: W = WET, D = DRY

AMBIENT TEMPERATURE: $21 \pm 2^\circ\text{C}$

PLAIN

REMARKS: UNJOINED PLOTS REPRESENT DRY AGGREGATE
WITH FIBERGLASS AT THE BOTTOM OF THE BEAM.

Figure 22. Flexural Strength Test Results (Continued)

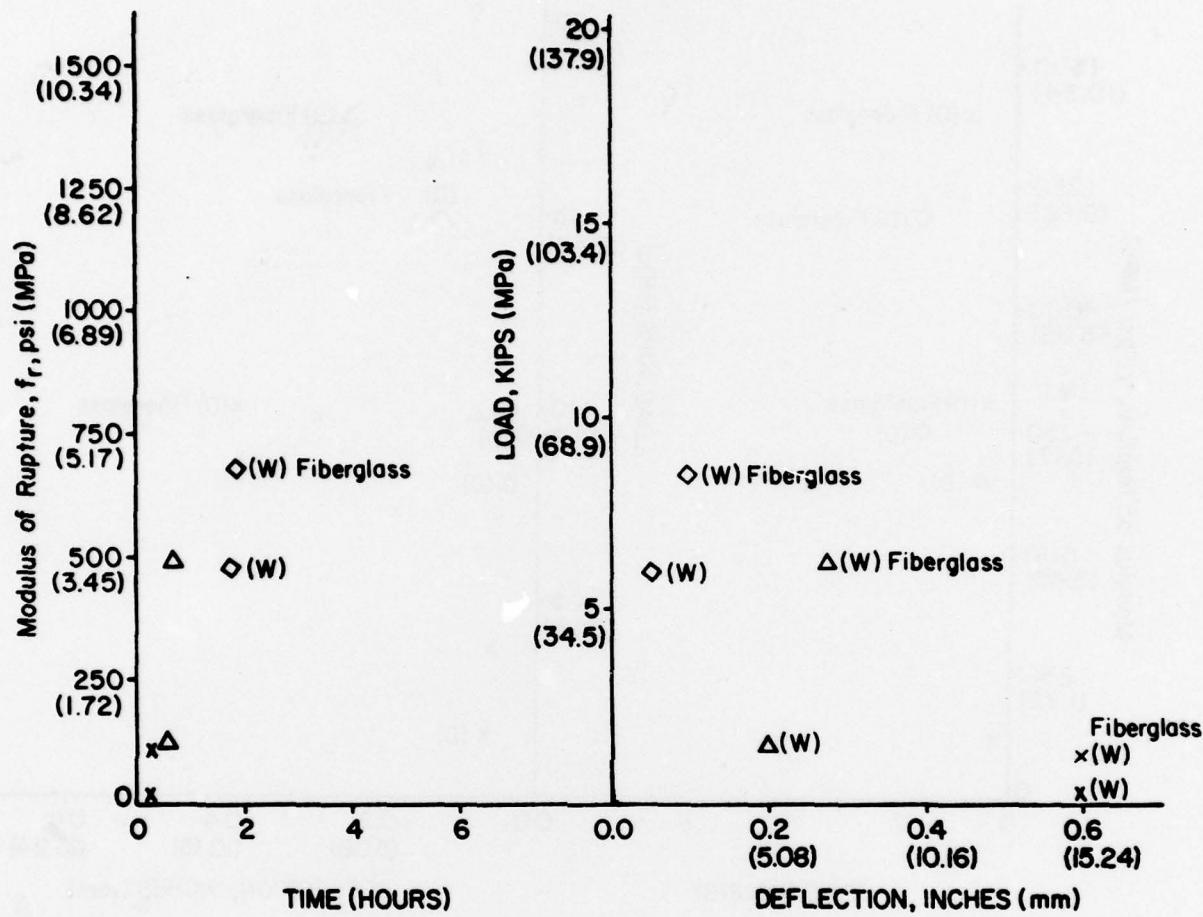


Figure 22. Flexural Strength Test Results (Continued)

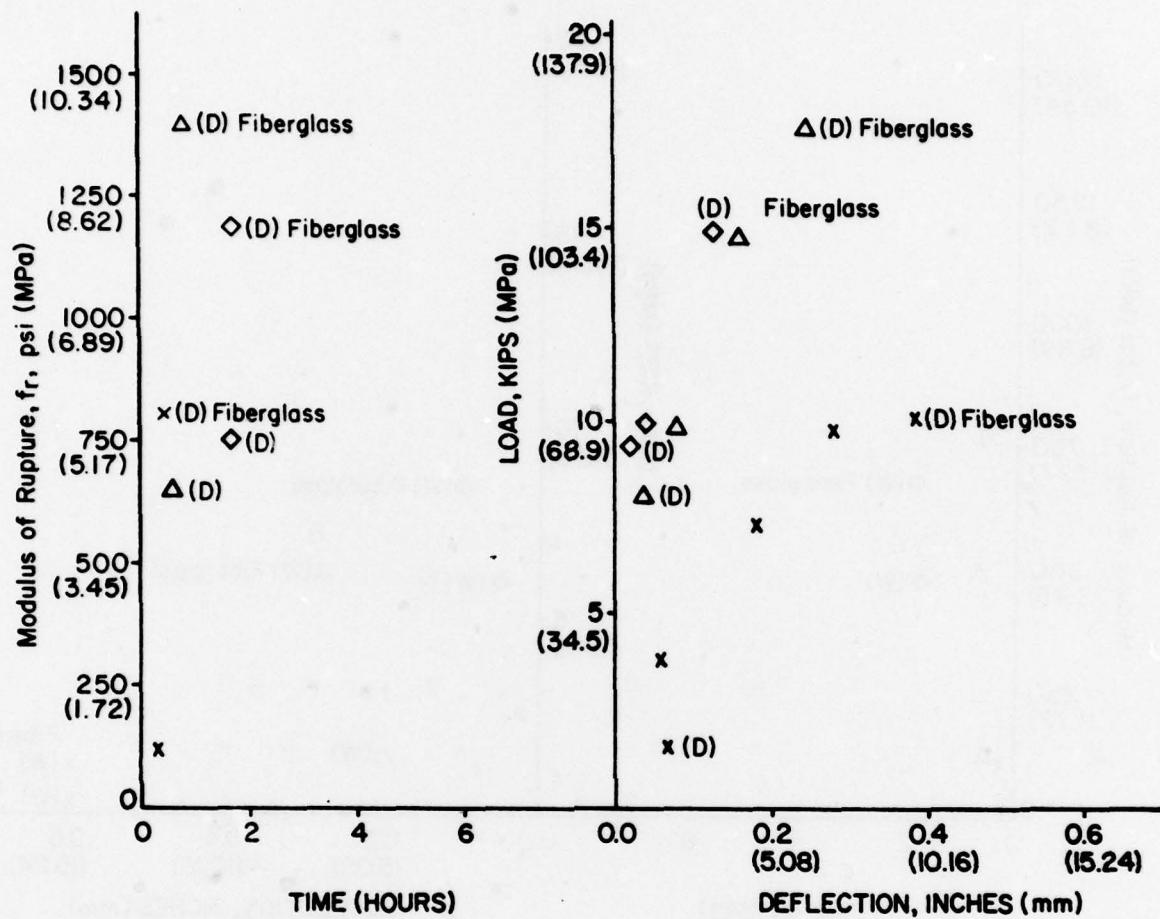


Figure 22. Flexural Strength Test Results (Concluded)

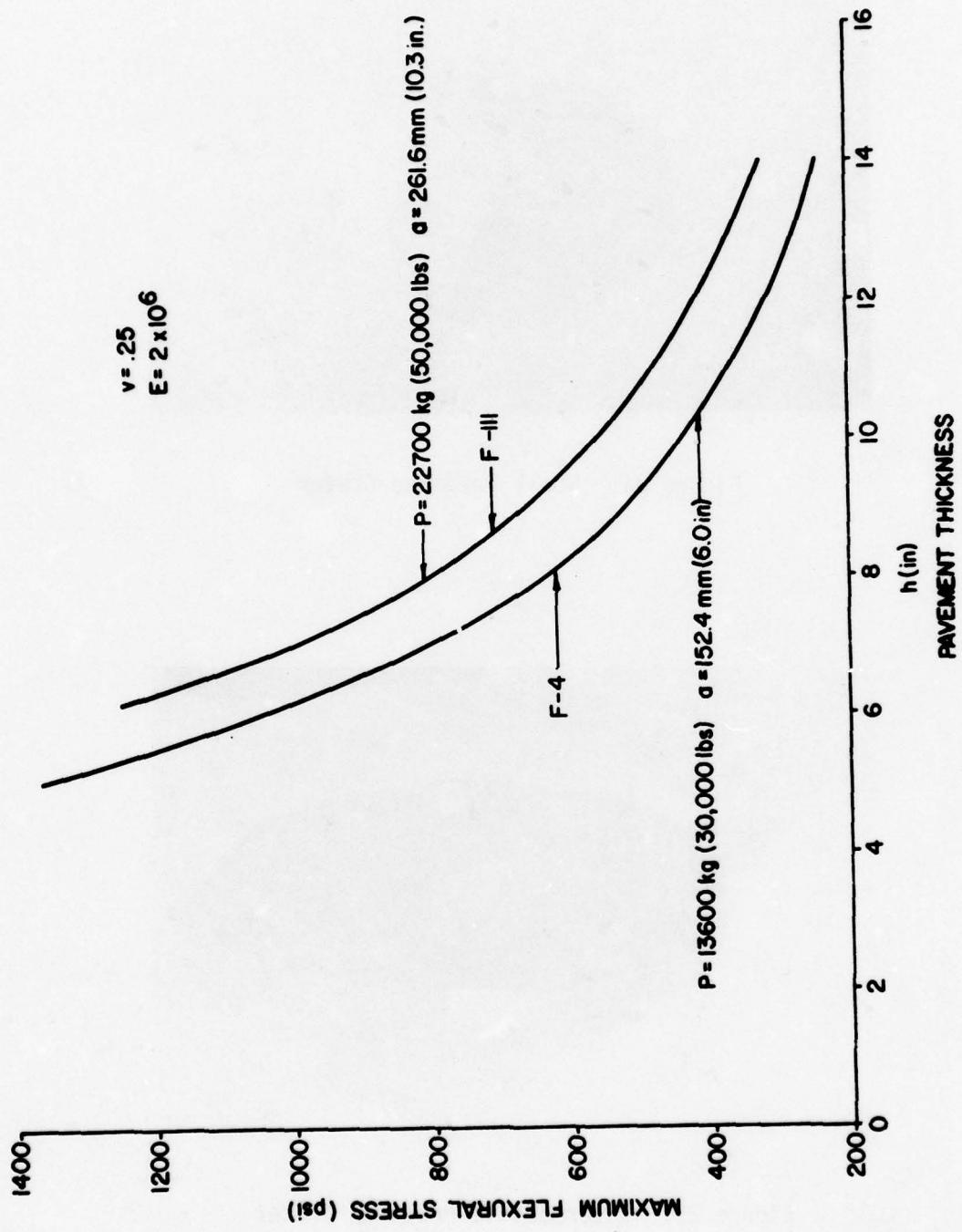


Figure 23. The Relationship Between Maximum Flexural Stress and Pavement Thickness. Infinite Plate on Elastic Foundation.

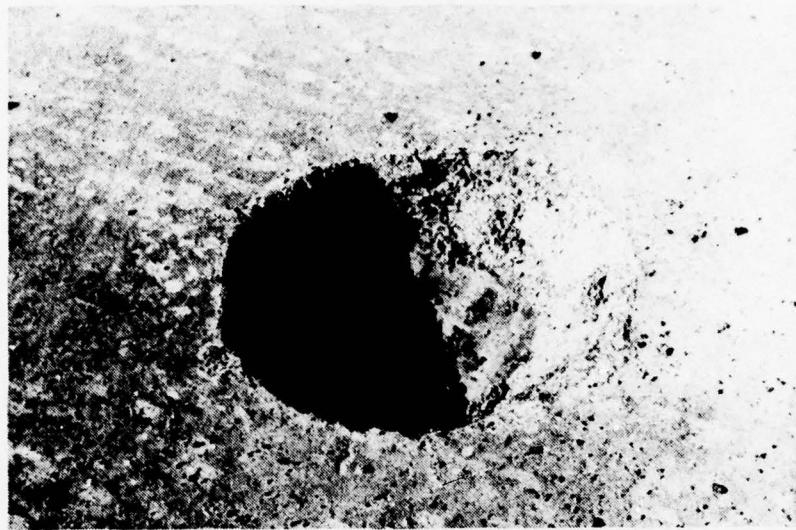


Figure 24. Small Prepared Crater



Figure 25. Intermediate Prepared Crater



Figure 26. Large Prepared Crater



Figure 27. Small and Intermediate Test Crater



Figure 28. Placement of Aggregate Into Crater



Figure 29. Levelling Aggregate with Surrounding Surface



Figure 30. Resin mixer (HES Fabricated)



Figure 31. Pouring Resin on Aggregate



Figure 32. Foaming Polyurethane Resin

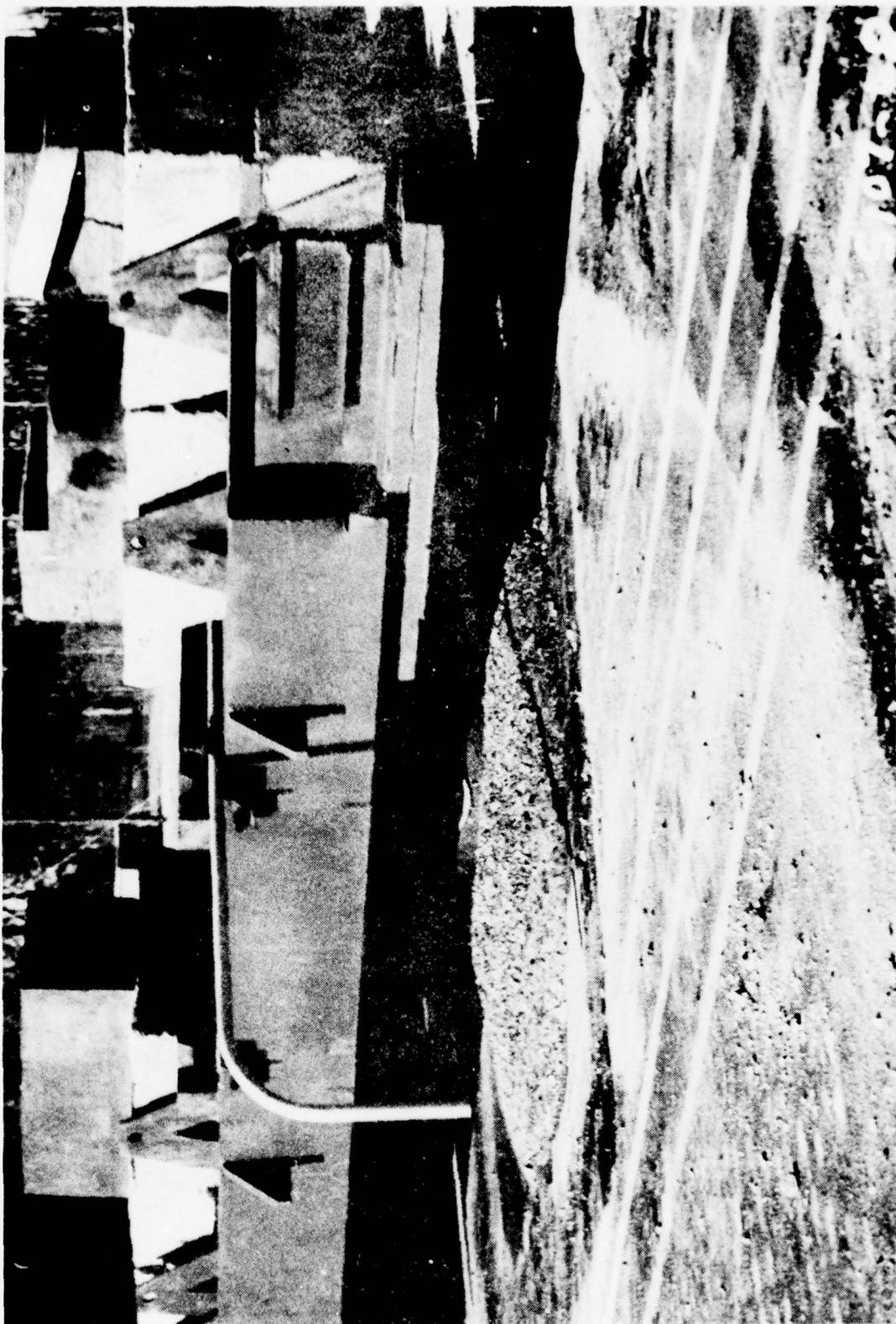


Figure 33. Initial Testing of Polyurethane Resin Cap with Load Cart

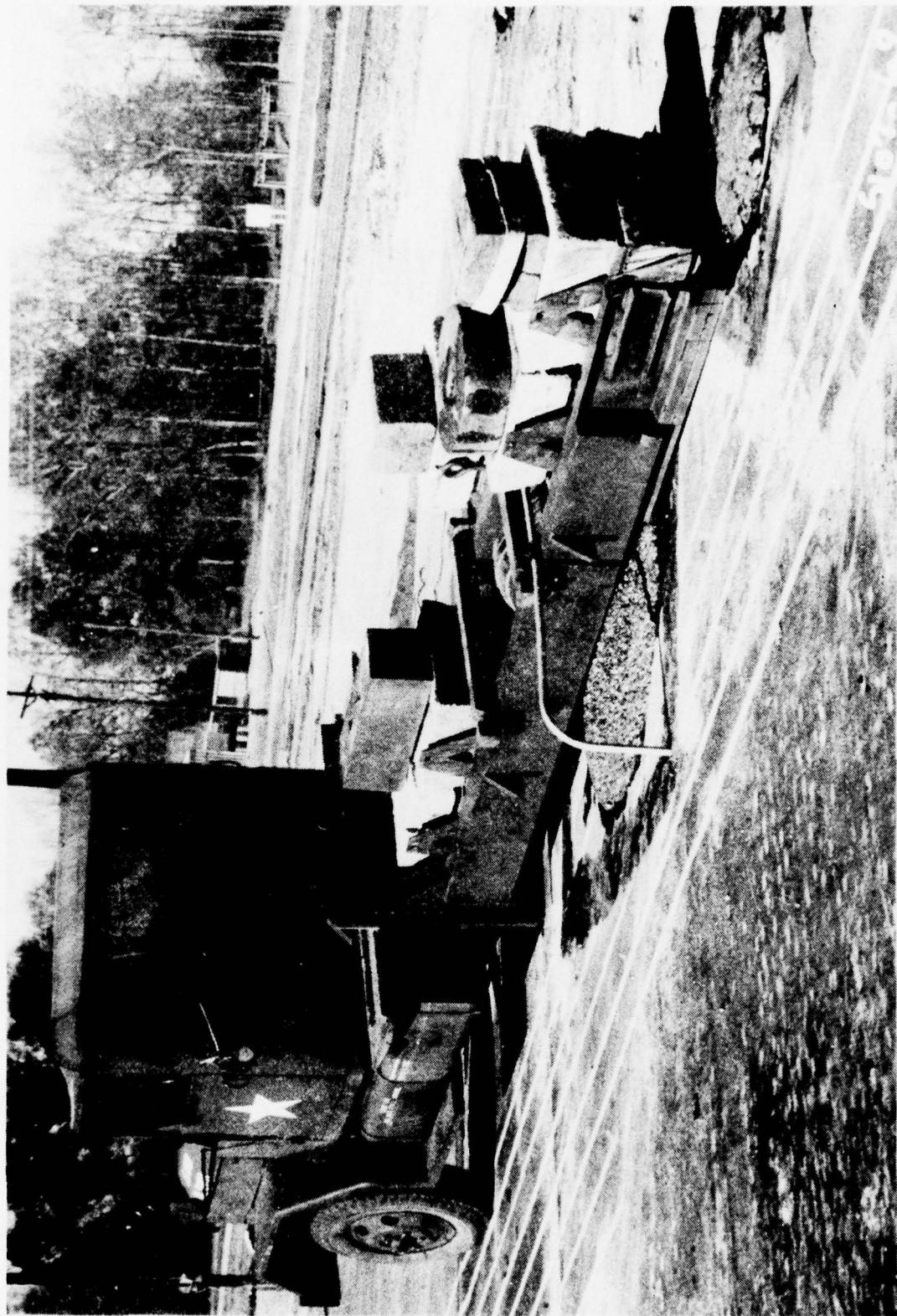


Figure 34. Failure of Polyurethane Resin Cap

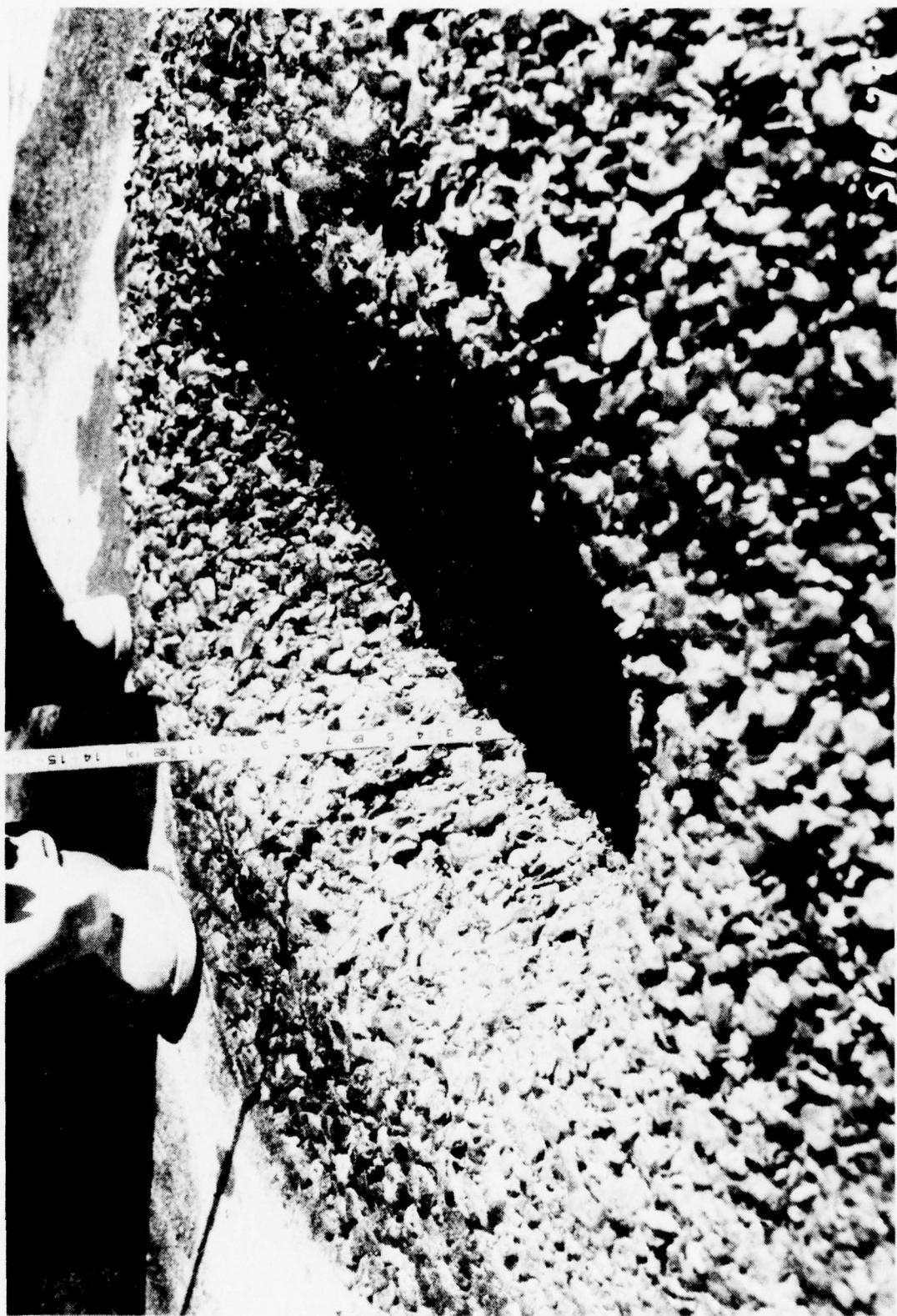


Figure 35. Indentation hole remaining after failure



Figure 36. Test Craters for Epoxy Resin

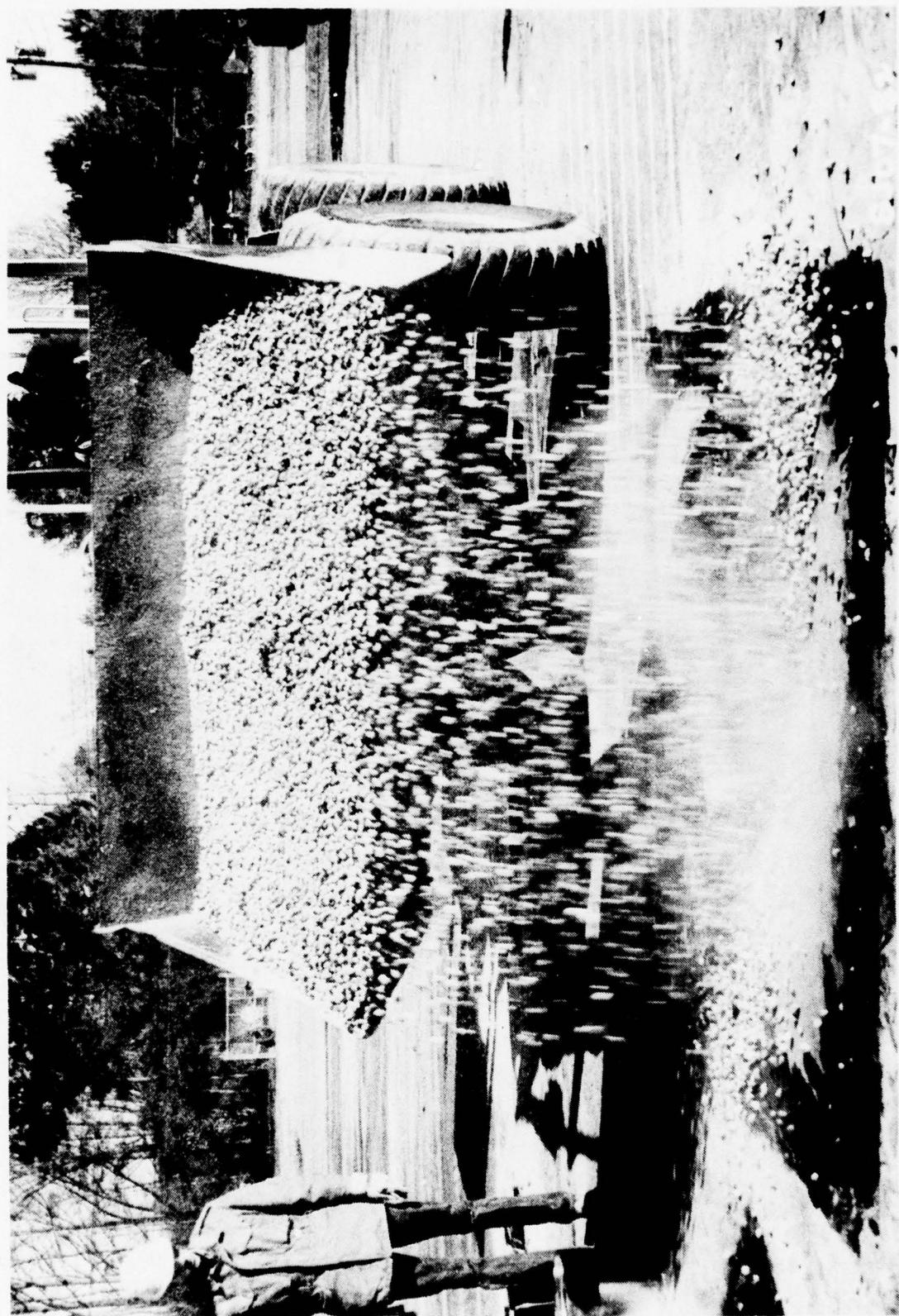


Figure 37. Aggregate Placement



Figure 38. Application of Epoxy Resin Mixture



Figure 39. Cured Epoxy Repair Cap



Figure 40. Epoxy Repair Cap After Required Test



Figure 41. Additional Loading Series Produced Ravelling (Loose Aggregate)



Figure 41. Additional Loading Series Produced Ravelling (Loose Aggregate)



Figure 42. Preparation of Polyester Repair Cap
(Intermediate Crater)



Figure 42. Preparation of Polyester Repair Cap
(Intermediate Crater) (Concluded)

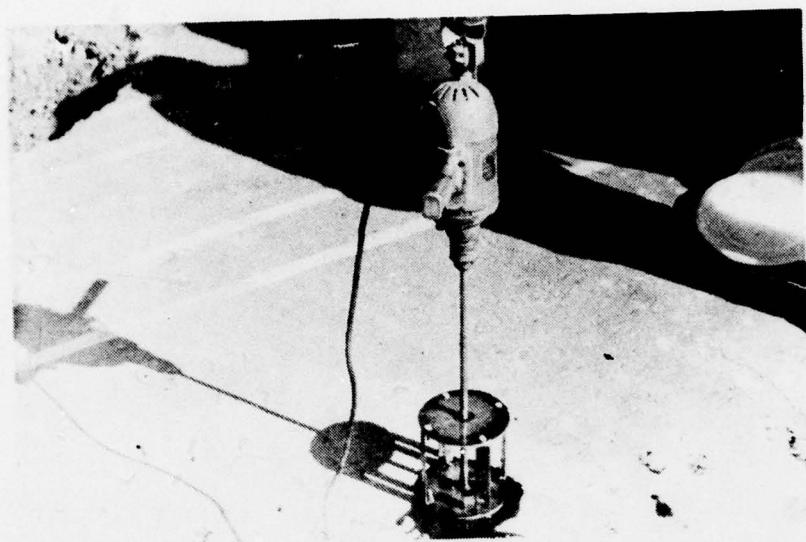


Figure 43. NES Mixer

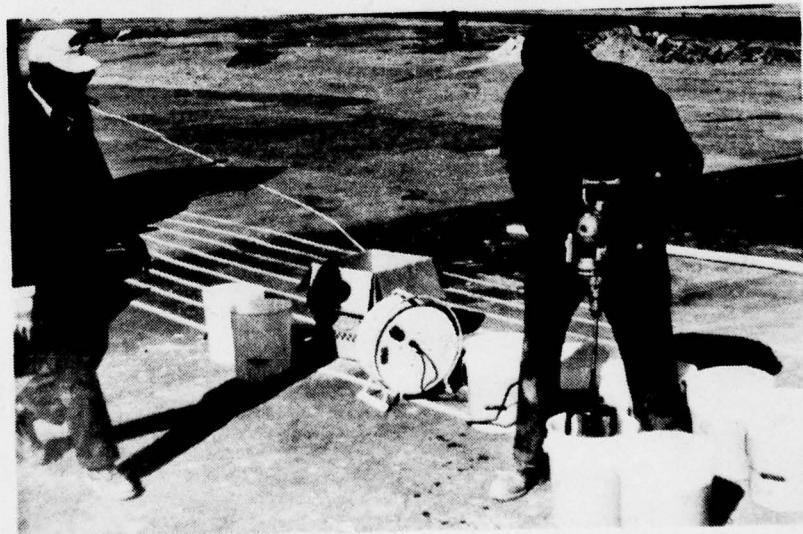


Figure 44. Mixing Polyester Resin Batch



Figure 45. Application of Polyester to Aggregate



Figure 46. Attempt to Remove Excess Resin

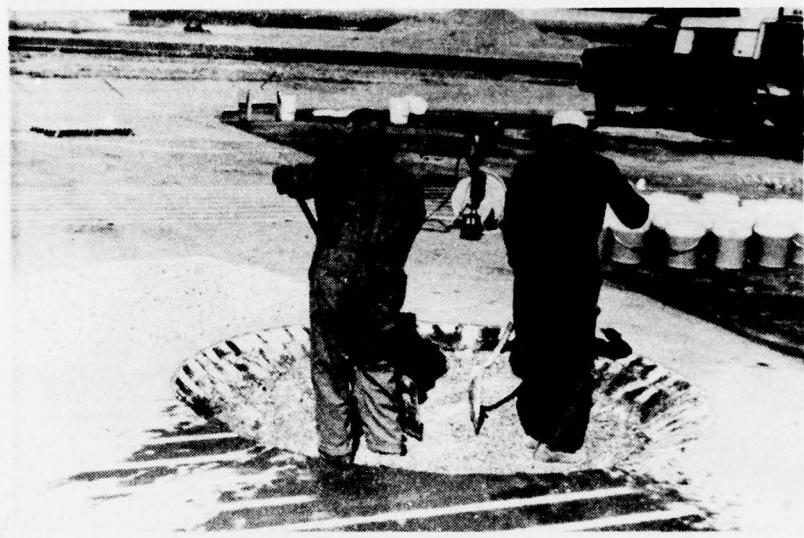


Figure 47. First Lift Filling of Large Crater



Figure 48. Installation of Fiberglass Cloth in Large Crater



Figure 49. Final Layer of Aggregate in Large Crater



Figure 50. Puddling of Excess Resin

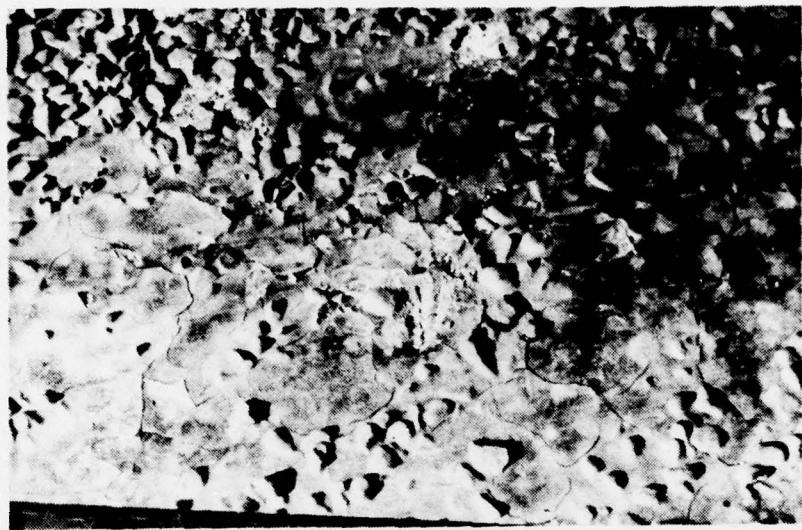


Figure 51. Thermal Cracking of Polyester Resin
(Surface Only)

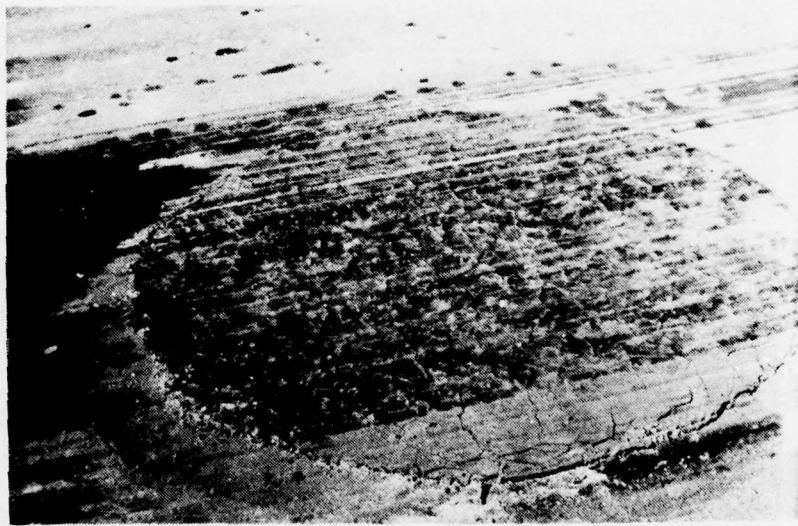


Figure 52. Intermediate Crater Polyester Repair Cap
After Required Loading Test Series



Figure 53. Small Crater Polyester Repair Did Not Bond to Edges



Figure 54. Small Crater Repair Removed



Figure 55. Large Crater Polyester Repair During Test Sequence

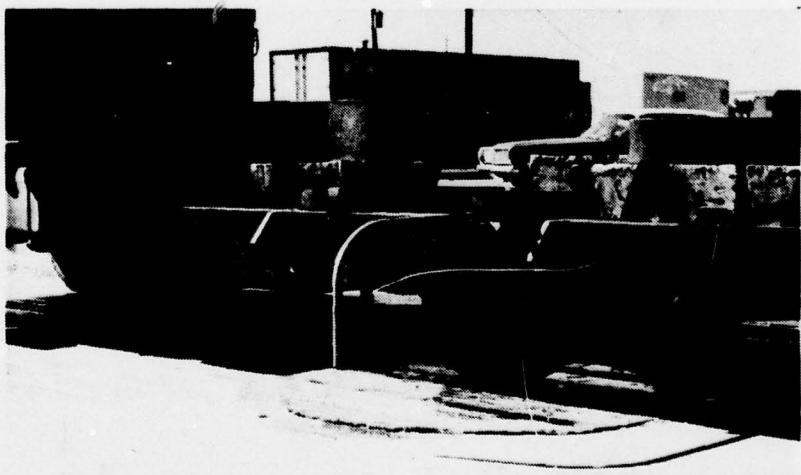


Figure 56. Note Lack of Bonding to Asphaltic Pavement Around Crater

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APPENDIX A
LITERATURE REVIEW

Present requirements for repairing bomb-damaged aircraft runways are completely described in Air Force Regulation 93-2 (Reference 8). That regulation prescribes the material, procedures, and personnel necessary to repair a maximum of three craters caused by 750-pound (340.9-kg) GP bombs dropped from attacking aircraft. Tests conducted during FY75 (Reference 9) determined that this repair procedure is adequate for the specified threat but not for other threats.

FAST-SETTING INORGANIC CEMENTS

The Western Company of Richardson, TX, reported on the development and field testing of a rapid-setting modified Portland Cement concrete which showed promise for rapid bomb-damage repair (References 10,11,12). The cement consisted of a mixture of calcium sulfate hemihydrate (gypsum), Portland Cement, and a proprietary product designated as TF-4 which served as a dispersing agent. This cement was designated "Fast-Fix." Laboratory tests were performed on both the Fast-Fix as a slurry (mixed with water only) and as a concrete (with sand and aggregate only). The slurry form demonstrated a 30-minute compressive strength of 3500 psi (24.1 MPa) and a flexural strength of 600 psi (4.1 MPa). The concrete form demonstrated a 30-minute compressive strength of 1800 to 2200 psi (12.4 to 15.2 MPa) and a flexural strength of 450 to 500 psi (3.1 to 3.4 MPa).

An actual-size, 750-pound (340.9-kg) bomb crater, 70 feet (21.3 meters) in diameter and 15 feet (4.6 meters) deep, was repaired as follows. Debris was used to backfill the crater to within 1 foot (0.3 meter) of the original runway surface. Because of the imposed time limitation--that an operational runway be produced within 1 hour after commencement of the repair work--the material was not extensively compacted. The only compaction was that provided by the rubber-tired road grader and front-end loaders as they moved about the crater in their normal filling and levelling activities. The remaining 1 foot (0.3 meter) was filled with a uniform aggregate having a void factor of 50 percent. Fast-Fix slurry was pumped over the aggregate and completely permeated the aggregate layer, giving an in-place concrete. A simulated fighter-aircraft moving-wheel load was successfully supported within 30 minutes after the crater was filled.

Repairs were also performed on simulated rocket craters 10 feet (3 meters) in diameter and 4 feet (1.2 meters) deep. These craters were first backfilled with aggregate to within 9 inches (228 mm) of the surface. The remaining depth was filled with Fast-Fix concrete placed from a conventional concrete transit-mix truck. The surface was screened and brushed before it hardened to give a nonskid surface. Simulated fighter-aircraft moving-wheel loads were successfully supported within 50 minutes after initiation of the repair work.

Further work was reported by the Western Company on efforts to improve the strength and durability of Fast-Fix concretes (Reference 13). These tests indicated that although Fast-Fix cements can be used for rapid repairs, they deteriorate rapidly and the repair cannot be considered permanent. The useful life of any repair depends on the environmental conditions at the repair site. It was also determined that Fast-Fix cements should not be used for structures in which the major portion of the load is a sustained dead load.

FAST-SETTING SYNTHETIC ORGANIC RESINS

Investigations by the Western Company also included studies using several organic materials as binders (References 11, 12). These materials included polyester, vinylester, and epoxy resins. The tests indicated that only the polyester resin would cure properly in the presence of water. The conclusion reached was that organic resins could be used for rapidly repairing bomb-damaged runways, successfully meeting all the rigid contract requirements that had been established. The contract also specified the development of a prototype machine for mixing and applying the resin. All field testing of the resins was performed on a small scale. However, an inorganic cement, FAST-FIX, was selected for full-scale testing because it was rated better in factors of material cost, shelf life, pumpability, and equipment simplicity.

Ashland Chemical Company of Columbus, OH, investigated the use of water-extended polyester (WEP) (Reference 14). Proper resin formulation eliminated the need for an emulsifying agent. Physical strengths of the resultant WEP composites were three to five times greater than values previously obtained using an emulsifier, with flexural strengths of 300 psi (2 MPa) and compressive strengths of 4800 psi (33 MPa). Field tests were conducted on two 4-foot x 5-foot (1.2- x 1.5-meter) slabs and the material successfully passed the 29,000-pound (13,181 kg) moving-wheel load test, but the subbase had been properly compacted prior to application of the resin. It was determined that WEP shrinks in time as the water is released from the matrix and does not have sufficient resiliency to prevent edge-failure problems. It was discovered, however, that WEP also failed to bond to the aggregate.

Raven Industries, Inc., of Sioux Falls, SD, investigated the use of wire-reinforced resin concrete for repair of craters from 750-pound (340.9-kg) bombs (Reference 15). A hole approximately 126 inches (3.2 meters) square was cut in an asphalt taxiway and excavated to a depth of 4 feet (1.2 meters). The hole was filled with 2 feet (0.6 meter) of sand and 21 inches (0.5 meter) of gravel which was then compacted by tamping. A polyethylene sheet was placed on top of the gravel, followed by a 3 x 8 No. 8 reinforcing cloth and 3 more inches (76 mm) of gravel. Deposition of the polyester resin took 15 minutes, and the resin took between 14 and 20 minutes to gel after it was poured. The polyethylene sheet was therefore necessary to retain the liquid resin at the top of the work. Fifty-three minutes after pouring, the repair failed to sustain a moving wheel load of 30,000 pounds (13,636 kg), rutting during the first pass. The wheel was buried in the surface by the end of the third pass. Examination disclosed that there was poor bonding of the resin to the aggregate in the lower half of the layer. Also, bonding of the resin to the wire reinforcement was poor, with large areas showing no attachment of the resin to the wire.

The fractured repair was removed from the hole, which was excavated to a depth of 3 feet (0.9 meter). Two feet (0.6 meter) of a 50-50 mix of sand and gravel were tamped thoroughly, after which a 6.5-inch (165-mm) layer of gravel was placed, followed by a 2.5-inch (63-mm) layer of packed sand and gravel. The polyethylene sheet and wire mesh were applied as before and were followed by the 3-inch (76-mm) layer of aggregate. Pouring of the resin was completed in 18.5 minutes. The resin started to gel 11 minutes after pouring was started, and gelling was completed 26 minutes after the initial pour. Testing, as before, was begun 64 minutes after pouring. In subsequent load tests there was no significant damage to the repair.

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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFIC--ETC F/G 11/4
RESIN CONCRETE FROM BOMB DAMAGE REPAIR OF AIRFIELD PAVEMENTS. (U)

NOV 77 A SMITH

MIPR-FQ8952-76-60007

UNCLASSIFIED

CEEDO-TR-77-53

NL

2 OF 2
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A073680

REF ID: A6124



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DATE
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The same resin formulation was used for both tests. The results indicated that thin resin-aggregate layers need extremely firm subgrades and complete filling of the aggregate voids by the resin as well as full bonding of the resin to the aggregate. Neither this observation nor the effect of the wire reinforcement on the strength of the repair was discussed in the report.

The Monsanto Research Corporation, Dayton, OH performed a study (Reference 16) to evaluate the work by Raven Industries and also to formulate and conduct an independent development effort toward the same goal. Several repair methods were demonstrated or investigated, most of which were eliminated from further study. Approaches evaluated were the use of a graded-density urethane foam, sulfur, a chemical grout, a liquid plug, thermosetting resins, pre-impregnated fiber reinforced sheets, Joosten-process solidification,* asphalts, calcium acrylate, calcium/lignosulfonate, fuel oil/molasses, quickset cements, epoxy resins, epoxy with expanded fillers, and resin/cement systems. Three systems best met the requirements of setting time, ease of application, and structure: epoxy/sand, epoxy-quick-set cement, and quick-set cement/sand. Further work would be needed to prove the full utility of these systems.

A study was performed by the Naval Civil Engineering Laboratory, Port Hueneme, CA (Reference 8) to evaluate through computer-based analytical procedures and through laboratory and small-scale field tests the effectiveness of conventional materials and methods for backfilling and repairing bomb craters in airfield pavements. The report recommends backfilling the crater with uniformly graded aggregate under constant subgrade for the final cap. Capping materials were not part of this investigation.

The University of New Mexico, Albuquerque, NM, performed a structural analysis to determine the required thickness of a resin cap for bomb crater repair (Reference 1). This work confirmed the prospect of using a 12-inch (0.3-meter) (or less) thick cap. Laboratory tests were performed on cast beams using uniformly graded aggregate and liquid resin binders. These tests indicated that some sort of membrane was needed below the aggregate layer to prevent draining of the resin from the aggregate before it gelled. Three methods were tested. First, a mat of woven roving fiberglass was placed 1/2 inch (13 mm) from the bottom of the beam. The mat was not soaked uniformly, and weak points developed in its plane, causing failure at low loads. Second, a filler of Cab-O-Sil was mixed with the resin to give high thixotropicity and fill the voids. This approach weakened the binder and caused erratic penetration. Third, a sand layer was placed beneath the aggregate. The liquid binder flowed uniformly over the surface of the sand and penetrated the entire layer, preventing loss of the resin and increasing the flexural strength in the layer.

* A soil-stabilization process wherein calcium chloride and water-glass solutions are pumped into a soil which must contain about 25 percent sand. The solutions react and form a binder.

Five resins were evaluated in the laboratory. Four had gel times from 1 to 12 hours, with cure times from 2 to 72 hours. The fifth, a polyester resin, had gel times from 5 to 15 minutes and cure times from 15 to 30 minutes, depending on the proportions of binder, catalyst, and promoter used.

A prototype field test was performed in which an actual crater which had been formed previously by exploding 15 pounds (6.8 kg) of C-4 84 inches (2.1 meters) below the surface of an 8-inch (203-mm)-thick pavement was used as the model. After excavation, this crater had a surface area of approximately 100 square feet (9.29 square meters) and a depth of 5.5 feet (1.7 meters). The crater was backfilled with silt to within 16 inches (0.4 meter) of the surface, which was compacted (to an average CBR of 6) in 12-inch (0.3-meter) lifts. Four inches (102 mm) of sand were then placed, followed by 12 inches (0.3 m) of 3/4-inch (19-mm) gravel. An epoxy resin was used, hand-mixed in steel barrels, and two test beams were poured in addition to the crater repair. The beams were tested on the day of the repair. The repair was tested the next day by trafficking with a wheel load of 30,500 pounds (13,863 kg). The cap successfully withstood 100 passes of the load without visible or measurable distress. Attempts to determine the load capacity of the cap were abandoned after it successfully withstood a load of 54,000 pounds (24,545 kg) applied over a 3-inch (76-mm)-diameter plate.

The use of plastic resins as binders for aggregate in low-temperature repairs was studied by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) (Reference 19). The report discusses the feasibility of using plastics at low temperatures and points out several potential problems, such as the difference in coefficient of expansion between aggregates and plastics. Another study at CRREL (Reference 20) pointed out the difficulties to be expected with some plastic and bituminous binders when applied at low temperatures.

APPENDIX B
MANUFACTURERS' ADDRESSES

Abatron, Inc.
P.O. Box 118
Elgin, IL 60120
409-426-2200

Abbott Laboratories
Chemical Marketing Div.
1400 Sheridan Rd.
N. Chicago, IL 60064
409-688-6100

Ablestik Laboratories
833 W. 182nd St.
Gardena, CA 90248
508-321-6252

Acme Chemicals Div.
Allied Products Corp.
P.O. Box 1404
New Haven, CT 06505
203-562-2171

Acme Resin Co.
1401 Circle Ave.
Forest Park, IL 60130
409-771-9680

Adhesive Engineering Co.
1411 Industrial Rd.
San Carlos, CA 94070
905-592-7900

Adhesive Products Corp.
1660 Boone Ave.
Bronx, NY 10460
903-542-4600

Akemi Plastics, Inc.
5265 S. Clinton Trail
Eaton Rapids, MI 48827
517-663-8191

Allaco Division
Bacon Industries, Inc.
192 Pleasant St.
Watertown, MA 02172
617-926-2550

Allied Chemical Corp.
Specialty Chemicals Div.
P.O. Box 1087R
Morristown, NJ 07960
201-455-2000

Alpha Chemical Corp.
P.O. Drawer A
Collierville, TN 38017
901-853-2615

American Cyanamid Co.
Industrial Chemicals &
Plastics Div.
Stamford, CT
203-348-7331

American Resin Corp.
4601 W. Pasadena Ave.
Wichita Falls, TX 76308
817-692-8011

Amicon Corp.
Polymer Products Div.
25 Hartwell Ave.
Lexington, MA 02173
617-861-9600

Anderson Development Co.
1415 E. Michigan St.
Adrian, MI 49221
517-263-2121

Anhydrides & Chemicals, Inc.
117 E. 18th St.
New York, NY 10003
903-684-4200

Applied Plastics Co.
P.O. Box 277
El Segundo, CA 90245
508-322-8050

Armstrong Products Co.
P.O. Box 657
Warsaw, IN 46580
219-267-3226

Ashland Chemical Co.
Div. Ashland Oil, Inc.
P.O. Box 2219
Columbus, OH 43216
614-889-3333

Atlas Minerals &
Chemicals Div.
ESB Inc.
151 Ash St.
Mertztown, PA 19539
215-682-7171

Axel Plastics Research
Laboratories, Inc.
41-14 29th St.
Long Island City, NY 11101
903-729-4646

BASF Wyandott Corp.
100 Cherry Hill Rd.
Parsippany, NJ 07054
201-263-0200

Beacon Chemical Co.
244 Lafayette St.
New York, NY 10012
903-226-6053

Berton Plastics, Inc.
170 Wesley St.
S. Hackensack, NJ 07606
201-488-6700

Bishop Electric
10 Canfield Rd.
Cedar Grove, NJ 07009
201-239-2400

Bostik Division
USM Corp.
Boston St.
Middleton, MA 09149
617-777-0100

Cadillac Plastic & Chemical Co.
1245 W. Fulton
Chicago, IL 60607
409-243-2500

Cal Polymers, Inc.
2115 Gaylord St.
Long Beach, CA 90813
508-436-7372

Carlson, R. H., Inc.
P.O. Box 191
Greenwich, CT 06830
203-661-9288

Castall, Inc.
Weymouth Ind. Park
E. Weymouth, MA 02189
617-337-6075

Celanese Coatings & Specialties Co.
Textile Chemicals Group
P.O. Box 506
Charlotte, NC 28201
704-596-3021

Celanese Resins
Div. Celanese Coatings Co.
11th at Hill St.
Louisville, KY 40208
502-585-8011

Chemical Coatings & Engineering Co.
221 Brook St.
Media, PA 19063
215-566-7470

Chemical & Engineering Associates
A Div. of PROCHEM, Inc.
Childs Rd, RD #3
Box 59A
Elkton, MD 21921
301-398-3133

Chemical Products Div.
CPL Corp.
King Philip Rd. E
E. Providence, RI 02914
401-434-1770

Ciba-Geigy Corp.
Plastics and Additives Div.
Saw Mill River Rd.
Ardsley, NY 10502
914-478-3131

Claremont Polychemical Corp.
501 Winding Rd.
Old Bethpage, NY 11804
516-420-1500

Conap, Inc.
1405 Buffalo St.
Olean, NY 14760
716-372-9650

Cook Paint & Varnish Co.
P.O. Box 389
Kansas City, MO 64141
816-471-4800

Daubert Chemical Co.
709 Enterprise Dr.
Oak Brook, IL 60521
409-986-4600

Deer Polymer Corp.
17 Industrial Dr.
Holden, MA 01520
617-829-6736

Dennis Chemical Co.
2701 Papin St.
St. Louis, MO 63103
314-776-1868

Devcon Corp.
Endicott St.
Danvers, MA 01923
617-777-1100

Diamond Shamrock Chemical Co.
2095 Danbury Pl.
Cleveland, OH 60172

Dow Chemical Co.
2020 Dow Center
Midland, MI 48640
517-636-5192

DuPont de Nemours
E. I. & Co.
1007 Market St.
Wilmington, DE 19898
302-774-2421

Durez Division
Hooker Chemicals & Plastics Corp.
602A Walck Rd.
N. Tonawanda, NY 14120
716-696-6000

Dynamit Nobel of American, Inc.
105 Stonehurst Ct.
Northvale, NJ 07647
201-767-1660

Emerson & Cuming, Inc.
869 Washington St.
Canton, MA 02021
617-828-3300

Eronel Industries
12607 Cerise Ave.
Hawthorne, CA 90250
508-772-6158

Fenewal, Inc.
400 Main St.
Ashland, MA 01721
617-881-2000

Flexcraft Industries
527 Avenue P
Newmark, NJ 07105
201-589-3403

Formulated Resins, Inc.
P.O. Box 508
Greenville, RI 02828
401-949-2060

Freeman Chemical Corp.
Div H.H. Robertson Co.
222 E. Main St.
Port Washington, WI 53074
414-284-5541

H. B. Fuller Co.
2400 Kasota Ave.
St. Paul, MN 55108

Furane Plastics, Inc.
5121 San Fernando Rd. W.
Los Angeles, CA 90039

General Electric Co.
Plastics Sales Dept.
1 Plastics Ave.
Pittsfield, MA 01201
413-443-5681

Georgia-Pacific Corp.
Chemical Division
900 SW Fifth Ave.
Portland, OR 97204
503-222-5561

B. F. Goodrich Chemical Co.
6100 Oak Tree Blvd.
Cleveland, OH 44131
216-524-0200

W. R. Grace & Co.
Marco Chemical Div.
1711 W. Elizabeth Ave.
Linden, NJ 07036
201-862-5600

Hardman, Inc.
Belleville, NJ 07109
201-751-3000

Hastings Plastics, Inc.
1704 Colorado Ave.
Santa Monica, CA 90404
508-829-3449

C. L. Hauthaway & Sons Corp.
638 Summer St.
Lynn, MA 01905
617-592-6444

Heil Process Equipment Co.
Div. of Dart Ind., Inc.
Avon, OH
216-777-5210

High Strength Plastics Corp.
1701 N. Damen
Chicago, IL 60647
409-278-3800

Hightemp Resins, Inc.
225 Greenwich Ave.
Stamford, CT 06902
203-357-7401

O. Hommel Co.
P.O. Box 475
Pittsburgh, PA 15230
412-923-2233

Hunt Process
Lawrence, MA
508-941-0231

Hysol Division
Dexter Corp.
15051 E. Don Julian Rd.
Industry, CA 91744

Inolex Corp.
Chemical Division
Jackson & Swanson Sts.
Philadelphia, PA 19148
215-271-6400

Interplastic Corp.
Commercial Resins Div.
2015 Broadway NE
Minneapolis, MN 55413
612-331-6850

IPRC Corp.
Bldg. #5
Harvreal Ind. Pk.
Farmingdale, NJ 07727

Ironsides Resins, Inc.
270 W. Mound St.
Columbus, OH 43216
614-224-2228

Isochem Resins Co.
Cook St.
Lincoln, RI 02865
401-723-2100

Jedco Chemical Corp.
601 MacQuesten Parkway N.
Mt. Vernon, NY 10552
914-664-7989

Key Polymer Corp.
Lawrence Ind. Park
Lawrence, MA 01842
617-683-9411

Koppers Co.
Organic Materials Div.
Elmhurst, IL
409-833-3380

Kristal Kraft, Inc.
900 Fourth St.
Palmetto, FL 33561
813-722-3206

Leepoxy Plastic, Inc.
3324 Ferguson Rd.
Baer Field
Fort Wayne, IN 46809
219-747-7411

M R Plastics & Coatings, Inc.
11460 Dorsett Rd.
Maryland Heights, MO 63043
314-291-0525

Metachem Resins Corp.
Mereco Products Div.
530 Wellington Ave.
Cranston, RI 02910
401-781-4070

Midwest Mfg. Corp.
Oak St. & Buff Rd.
Burlington, IA 52601
319-754-8474

Miller-Stephenson Chemical Co., Inc.
George Washington Highway
Danbury, CT 06810
203-743-4447

Mitchell Rand Mfg. Corp.
Torne Valley Rd.
Hillburn, NY 10931
914-357-2700

Mobay Chemical Corp.
Pittsburgh, PA 15205
412-923-2700

Mol-Rez Division
Whitaker Corp.
3134 California St.
Minneapolis, MN 55418
612-781-4833

Monsanto Company
800 N. Lindbergh Blvd.
St. Louis, MO 63166
314-694-1000

N.L. Industries, Inc.
Industrial Chemicals Div.
Wycoff Mills Rd.
Hightstown, NJ 08520
609-448-3200

Olin Corp.
Chems Group
120 Long Ridge Rd.
Stamford, CT 06904
203-356-2872

Pacific Resins and Chemicals, Inc.
1754 Thorne Rd.
Tacoma, WA 98421
206-572-8181

Palmer Products, Inc.
Worcester, PA
215-584-4241

Plastics Engineering Co.
3518 Lakeshore Rd.
Sheboygan, WI 53081
414-458-2121

Polymer Systems Corp.
135 Stevens Ave.
Little Falls, NJ 07424
201-256-7850

Polyproducts Corp.
13810 Nelson Ave.
Detroit, MI 48227
313-931-1088

Poly Resins
P.O. Box 158
Sun Valley, CA 91352
508-768-6600

Polyrez Co.
S. Columbia St. RR
Woodbury, NJ 08096
609-845-1813

PPG Industries, Inc.
Chemical Division
Pittsburgh, PA
412-274-4500

Proctor & Gamble
Industrial Chemical Division
P.O. Box 599
Cincinnati, OH 45201

Purethane Division
Easton RS Corp.
4907 Farragut Rd.
Brooklyn, NY 11203
903-629-0920

Permuthane
Corwin St.
Peabody, MA 01960
617-531-188-

Quaker Oats Co.
Chemicals Div.
Merchandise Mart Plaza
Chicago, IL 60654
409-222-7111

K. J. Quinn & Co.
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Malden, MA 02148

Reichold Chemicals, Inc.
601-707 Woodward Hts. Blvd.
Ferndale, MI 48220
914-682-5700

Ren Plastics
5656 S. Cedar St.
Lansing, MI 48909
517-393-1500

E. V. Roberts & Assoc.
Resin Formulators Co.
Div. Evra, Inc.
9601 Jefferson Blvd.
Culver City, CA 90230
800-421-0824

Royston Laboratories, Inc.
Columbia Technical Corp.
Pittsburgh, PA
412-828-1500

Ruco Division
Hooker Chemical Co.
New South Road
Hicksville, NY 11802
516-931-8100

Shell Development Co.
P.O. Box 1380
Houston, TX 77001
409-325-6860

Silmar Division
Vistron Corp.
12335 S. Van Ness Ave.
Hawthorne, CA 90250
508-757-1801

Smooth-On, Inc.
1000 Valley Rd.
Gillette, NJ 07933
201-647-5800

Solar Compounds Corp.
P.O. Box 227
Linden, NJ 07036
201-862-2813

Sta-Crete Co.
893 Folsom St.
San Francisco, CA 94107
905-982-3067

Stanchem, Inc.
401 Berlin St.
E. Berlin, CT 06023
203-828-6351

Sterling
Div. Reichold Chemicals, Inc.
814 Commerce Dr.
Oakbrook, IL 60521
409-887-0315

Stonhard Co.
Maple Shade, NJ
609-779-7500

Sullivan Chemical Coatings
410 N. Hart St.
Chicago, IL 60622
409-666-8080

Synres Chemical Corp.
1211 N. Olive
P.O. Box 3400
Anaheim, CA 92803
508-722-1834

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3M Company 3M Center Bldg. 223-6NE St. Paul, MN 55101 612-733-1110	Verona Division Mobay Chemical Corp. P.O. Box 385 Union, NJ 07083 201-686-3700
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U.S. Polymeric Div. Hitco P.O. Box 2187 Santa Ana, CA 92707 714-549-1101	Shaefer Chemicals, Inc. P.O. Box 132 Riverton, NJ 08077 607-829-0200
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